BILINGUALISM AND COGNITIVE CONTROL: A COMPARISON OF SEQUENTIAL AND SIMULTANEOUS BILINGUALS

by

Jin Bi

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STATEMENT OF DISSERTATION APPROVAL

The dissertation of **Jin Bi**

has been approved by the following supervisory committee members:

Mary Ann Christison	, Chair	**Feb. 16, 2017** Date Approved
Adrian Palmer	, Member	**Feb. 16, 2017** Date Approved
Marianna Di Paolo	, Member	**Feb. 16, 2017** Date Approved
Jason Watson	, Member	**Feb. 16, 2017** Date Approved
Ellen Knell	, Member	**Feb. 16, 2017** Date Approved

and by **Patricia Hanna** , Chair/Dean of

the Department/College/School of **Linguistics**

and by David B. Kieda, Dean of The Graduate School.

ABSTRACT

It has been acknowledged in the research on bilingualism that bilingual speakers, regardless of age, exhibit enhanced cognitive control capacity (e.g., interference control) as compared with their monolingual peers. Behavior and imaging studies suggest that these effects are the result of a shared neural network recruited by both linguistic processing and general-purpose cognitive control in bilinguals. The majority of studies on bilingual cognitive control examine two groups—an early bilingual group (individuals who have been exposed to two languages from a very early age) vs. a monolingual control group. Late bilinguals (i.e., people who acquire a second language later in life) are often excluded in studies of bilingual cognitive control. Yet it is precisely this population that makes up the majority of bilinguals in United States. This dissertation study compares an early bilingual group with two late bilingual groups in order to examine whether the cognitive processing advantage observed in bilinguals was associated with age of acquisition (AOA) or language proficiency. Data on cognitive control capacity were collected through three lab tasks that measured working memory capacity (WMC), response inhibition, and interference control, respectively. Results found that successful inhibition of prepotent responses was associated with higher WMC, later AOA, and higher language proficiency, while successful interference suppression was associated with higher WMC, earlier AOA, and higher language proficiency. An efficient speed-accuracy trade-off pattern was also observed in early bilinguals. Findings from this study are discussed under the framework of the adaptive control hypothesis.

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CHAPTER 1

INTRODUCTION

The ability to speak languages other than one's mother tongue has always been cultivated and encouraged in human history. In ancient China, foreign language classes were a part of the curriculum of an 8-year-old in the Han Dynasty (206 BC – 220 AD). The first-century Roman writer Gellius noted in his book that the famous king Mithridates was fluent in 25 languages. At present, it is estimated that at least half of the world's population is bilingual (Grosjean, 2010, p. 13). This percentage is no surprise for the Europeans. The 2006 Eurobarometer survey found that 56% of Europeans were fluent speakers of one foreign language or more, 28% were capable of speaking at least two, and a further 11% could converse in no less than three foreign languages (Extra & Gorter, 2008). Even the 2007 American Community Survey reported that about 20% of Americans spoke a language other than English at home, which was a 140% increase compared with the 1980 data (Shin & Kominski, 2010). In the state of Utah, the proportion of bilingual speakers can be expected to grow rapidly in the future, as 163 schools in this state offer dual language immersion programs in the 2016-2017 school year (Utah State Office of Education, 2017).

The numbers mentioned above suggest that multi-language use is the norm in human communities. Indeed, anthropologists (e.g., Hirschfeld, 2008) proposed that the ability to learn new languages provides humans with a surviving edge in evolution. It is not clear historically how bilinguals and multilinguals made better survivors, but there are a few obvious societal advantages. Most people are aware of the career benefits associated with speaking a second language (L2). However, recent research found that in addition to language-associated benefits, such as superior metalinguistic awareness (i.e., an understanding of language and how it works), people who grow up speaking two language show better performance in tasks that reflect nonlinguistic cognitive functions of the brain, such as interference control; and these people have better resistance to dementia in old age. (For reviews, see Akhtar & Menjivar, 2012; Bialystok & Craik, 2010.) Furthermore, the cognitive benefits of L2 learning cited above are additive and at no cost of the L1 development. Specifically, it has been demonstrated that majority language students in immersion programs (e.g., Chinese students in China learning English) are able to keep pace with their monolingual peers when it comes to first language (L1) literacy development (i.e., reading and writing) (Chiappe, Glaeser, & Ferko, 2007; Chiappe & Siegel, 1999; Chow, McBride-Chang, & Burgess, 2005; Loizou & Stuart, 2003).

The exact mechanisms underlying the bilingual advantage are not yet fully understood, but they very likely arose out of a lifetime's experience of juggling two languages in the brain. Bialystok and Hakuta (1994) hypothesize that "…the representation that bilingual speakers construct for their two languages may include two components, a common representation that is the record of general linguistic knowledge and separate representations that record language-specific information" (p. 119). This explanation is supported by the evidence that even when one language is in use, both languages are simultaneously activated in the brains of bilinguals (e.g., Linck, Kroll, & Sunderman, 2009). Therefore, being a bilingual means having a brain that is constantly involved in code-switching (i.e., activating one language representation while inhibiting another), which is a challenging task for the human brain with its limited attentional control resources.

The positive transfer from language skills to nonlinguistic tasks found in the literature is evidence of a shared cognitive control network in the brain. It is highly likely that the bilingual cognitive benefits may come as a result of a superior general executive function (in this study, "executive function" is used interchangeably with cognitive control, which refers to higher cognitive functions that make us human, such as planning, problem solving, etc.) network that is beyond the traditional "language regions" in the brain. The argument made by Green and Abutalebi (2013) is that "[I]ncreased cognitive demands associated with language control in bilingual speakers lead to enhanced skills in cognitive control and these enhanced skills are deployed in performing nonverbal tasks tapping such control" (p. 515).

The majority of studies on bilingual cognitive control examines two groups (i.e., a bilingual group vs. a monolingual control group), and the bilinguals that participated in these studies are usually simultaneous or early bilinguals who have been exposed to the two languages at home from birth or from a very early age (Hilchey & Klein, 2011, pp. 630-631). The sequential or late bilinguals, people who acquire a second language later in life (often as a result of study in a foreign language classroom), are proficient second language users but may not be considered fully bilingual by some definitions and, therefore, are often excluded in the studies on the cognitive benefits of bilingualism. Yet it is precisely this population that makes up the majority of bilinguals in United States (the 2007 American Community Survey quoted above found that only 20% were possible simultaneous bilinguals). The percentage remains low because not everyone has parents who speak languages other than English at home on daily basis. In addition, before the 1980s, there were few dual immersion programs available in public schools in the U.S (Center for Applied Linguistics, 2011). At present, immersion programs usually start in first grade so these students would not be considered simultaneous bilinguals by most definitions. Therefore, the general public does not have many opportunities to learn foreign languages from an early age.

It is also true that when students receive continued foreign language training in school, some of them eventually become fluent speakers of the target language, even if they start learning a foreign language relatively late in life (Singleton, 2001). Therefore, if this group of sequential bilinguals can cognitively benefit from classroom L2 learning, it would suggest that foreign language education should be a vital part of K-12 education and even college education. Because the learning of another language can promote the development of cognitive abilities related to problem solving and decision making, both of which belong under the umbrella term executive functions or cognitive control.

There have been a number of studies that have compared the development of language proficiency and cognitive processing in L2 learners with different language experiences (e.g., study abroad vs. traditional classroom instruction), but findings on cognitive outcomes remained inconclusive (e.g., Linck, Hoshino, & Kroll, 2008; Linck et al., 2009; Sunderman & Kroll, 2009). Cummins (1976) suggested in his threshold hypothesis that a balanced command of two languages is the prerequisite for positive transfer to cognitive processing to occur, and this hypothesis is examined in the current research. In the current study, the effect of L2 learning on cognitive control was explored by comparing three language learning groups using a cross-sectional research design: the late high proficiency bilinguals (i.e., late bilinguals who self-rated themselves as highly proficient in their L2), the late low proficiency bilinguals group (i.e., late bilinguals who self-rated themselves as not proficient in their L2), and the early bilingual group. Such a comparison makes it possible to look into whether or not sequential bilinguals enjoy the same cognitive benefits as simultaneous bilinguals, and whether or not enhanced executive functioning is correlated with the age of acquisition and foreign language proficiency or simply with innate working memory capacity, which is an indicator of both verbal working memory capacity and language aptitude (Daneman & Merikle, 1996).

An issue that has not been adequately addressed in the bilingual cognitive control literature is the difficulty of finding a reliable and lasting bilingual advantage on non-linguistic interference tasks in young adults (see Hilchey & Klein, 2011, p. 654). This result could reflect a strategy or processing difference between bilinguals and monolinguals that is only apparent when the task has not been practiced. It could also be due to the fact that young adults are at the prime of their cognitive control and that any processing advantages in bilinguals could be made up by monolinguals through the recruitment of additional brain networks. Putting it simply, under certain conditions, monolinguals can use the strategy of recruiting more attentional control resources to achieve the same performance on cognitive tasks as bilinguals. If this is the case, then it is possible to make cognitive processing differences between bilinguals and monolinguals emerge in behavior tasks when the experiment task is made more demanding for both groups.

In order to increase task difficulty, an experimental change was made in the instructions given to the participants when they begin the Simon task (see Chapter 3 for details). The task instructions were modeled after the Stroop study by Kane and Engle (2003) and added an emphasis of staying on task, thereby encouraging exertion of cognitive control in participants. If simultaneous bilinguals enjoy greater cognitive control flexibility over sequential bilinguals, this experimental change should make the cognitive processing differences among these groups apparent in behavior studies.

The present study examined the differences among the early bilingual group and the two late bilingual groups relative to their language proficiency and executive functioning. Data were collected from young college adults. This study attempted to provide an explanation of the cognitive control differences among simultaneous bilingual and two types of sequential bilinguals with varying levels of language proficiency and, thereby, extend our understanding of the cognitive benefits of learning new languages.

CHAPTER 2

REVIEW OF THE LITERATURE

This chapter starts by reviewing classifications of bilinguals for the purpose of demonstrating that conceptualizations of bilingualism are varied and have historically been so, and then defining the types of bilinguals associated with the present study. This is followed by a summary of the effects of foreign language learning contexts on learning outcomes. Next, models of bilingual language representation and processing are compared. The review of the models is followed by reviews on neuroimaging studies on adult second language acquisition and empirical research on bilingualism and cognitive control. Finally, research questions and hypotheses for the current study are presented.

Conceptualizing Bilingualism

Concerns about bilingual education can be traced to the first century when people in Rome argued about which language, Greek or Latin, should be first taught and how they should be taught (Harris & Taylor, 2005). More than 2000 years later, discussions about bilingual education and the development of bilingualism remain a primary concern for many researchers. Past decades have witnessed a rapid development in technology and dramatic changes in the focus of research, with the focus shifting from language differentiation (i.e., when and how children differentiate between their two languages and when they mix linguistic elements) (Genesee, Nicoladis, & Paradis, 1995) to issues of cross-linguistic influence. In recent years, researchers in bilingualism have also begun to focus on understanding the relationship between language and cognition in bilinguals (Bhatia & Ritchie, 2013).

In addition to shifts in the research orientations in bilingualism, definitions or conceptualizations of bilingualism have also gone through changes. Early notions of bilingualism (Bloomfield, 1933) were understood as use of two languages with the addition of a second language that was equal to one's own native language. Weinreich (1953) succinctly mentioned that, "the practice of alternately using two languages will be called BILINGUALISM, and the persons involved, BILINGUAL" (p. 1). Indeed, many definitions of bilingualism were restricted to equal mastery of two languages; however, researchers found that native-like proficiency in both languages, which is sometimes described as true bilingualism, is rare (Cutler, Mehler, Norris, & Segui, 1992; Grosjean, 1982). Later definitions of bilingualism have included notions of the unequal mastery of two languages (Bhatia & Ritchie, 2004). For example, bilinguals are those who are fluent in one language but who "can produce complete meaningful utterances in the other language" (Haugen, 1953, p. 7). From this view, balanced and dominant bilinguals are distinguished according to the language proficiency in each language. Balanced bilinguals are regarded as those who are equally fluent in both first language (L1) and second language (L2) (e.g., children who acquire two languages from birth) while dominant bilinguals are those individuals who have varying levels of L2 proficiency, and those levels are not the same as the L1. However, there are more dominant bilinguals than balanced bilinguals because people rarely use two languages in exactly the same situation

(Myers-Scotton, 2006; Peal & Lambert, 1962). For example, some bilinguals may be balanced in terms of basic interpersonal communication skills (BICS) (Cummins, 1979, 1980a, 1980b) but may be not be balanced relative to cognitive academic language proficiency (CALP).

Because of the multidimensionality of bilingualism, bilinguals can be further classified. For example, based on the age of acquisition (AOA) (also known as age of onset), bilinguals are categorized into simultaneous, sequential, and late bilinguals. Simultaneous bilinguals are exposed to two languages from birth. A child who is introduced to an L2 after the L1 has been firmly established, at the age of around 3, is considered a sequential bilingual, while people who begin to be exposed to L2 after puberty or in adulthood are considered late bilinguals (Genesee et al., 1978).

Bilinguals may also be categorized as receptive and productive based on their functional abilities. Receptive bilinguals are those who can understand considerably more than they can produce in the L2 either in oral or written domains, while productive bilinguals can both understand and produce in the L2 (Butler, 2013). Researchers have also made a distinction among compound, coordinate, and subordinate bilinguals according to the organization of linguistic codes and units of meaning (Ervin & Osgood, 1954). The term compound bilingual has been referred to as an individual who has one semantic system but two linguistic codes. The reference is usually reserved for the children (and less often adults) who learn two languages at the same time, often in the same context. Coordinate bilinguals are individuals who are thought to have two semantic systems and two linguistic codes, resulting from learning two languages in distinctively separate contexts. Subordinate bilinguals are those who have one weaker and one stronger language, and they often use the stronger language to interpret the weaker one (Weinreich, 1953).

Researchers have also categorized bilinguals as elite or elective and as folk or circumstantial. These distinctions are based on language status and learning environments. Elite or elective bilinguals are those who choose to have a bilingual home in order to enhance social status, while folk or circumstantial bilinguals are those who have to learn an L2 because the dominant society marginalizes the value of the L2 as a language with minority status (Fishman, 1977; Valdés & Figueroa, 1994).

Additive and subtractive bilinguals are distinguished on the basis of the effects of the L2 learning on the retention of L1 (Lambert, 1974). People are considered additive bilinguals when L2 learning does not interfere with L1 learning. In other words, two languages, the L1 and the L2, are developing side by side. In contrast, people are considered subtractive bilinguals when L2 learning interferes with L1 learning, and as a result, the L2 replaces the L1 over time, such as in the case of international adoptees. Table 2.1 provides a summary of the various types of bilinguals in relationship to criteria used for classification.

However, a comprehensive definition of bilingualism is obviously more complex than a simplistic categorization. Gottardo and Grant (2008) proposed a continuum for bilingualism because some bilinguals may have varying degrees of bilingualism, and they may be more accurately characterized as multilinguals with varying degrees of proficiency in two or more languages in addition to their dominant language. Furthermore, bilinguals' mastery of the four language skills (i.e., reading, listening, speaking, and writing) may not be balanced; for example, one skill can be better developed than others. In conceptualizing bilingualism, these factors cannot be overlooked. As noted by many researchers (e.g., Butler, 2013; Gottardo & Grant, 2008), bilingualism is a highly complex social, psychological, and linguistic phenomenon, and needs to be understood from a multidimensional aspect. Both linguistic and nonlinguistic factors should be considered, such as purposes of using two languages, age of acquiring the second language, continued exposure to the first language, relative skill in each language, and the context in which each language is learned. Therefore, broad definition of bilingualism can help not only to gain a comprehensive understanding of bilingualism, but also be useful in examining the dynamics of language abilities and language use across contexts and times.

This study is primarily concerned with bilingualism as it relates to age of acquisition, as well as L2 proficiency. Three groups of college bilingual students were recruited. The early bilingual group (EB) is comprised of individuals who were exposed to two languages before the age of 3 (this is the generally accepted age in the field) and are fluent speakers of both languages. In addition, the EB has used both languages actively in their lifetime on a regular basis. The other two groups are referred to as the late high proficiency bilinguals (LH) and the late low proficiency bilinguals (LL) because they started learning a new language after aged 5 (see Chapter 3 for detailed descriptions). The difference between the two late bilingual groups is their language proficiency. The next section reviews studies on the context of foreign language learning.

Language Learning Context and Its Effect on Acquisition

The context of learning a language has been viewed as one of the crucial variables in second language acquisition (SLA) and has been a focus of considerable research

(Freed, 1995a). Researchers have placed emphasis on similarities and differences in acquisition between language learning and various learning contexts. These contexts include the immersion classroom settings (IM), the traditional or formal language classroom (FC) setting at one's home country (also called AH), and the study abroad environment (SA). Immersion classrooms focus on learning grade level content in the target language. In addition, instruction should be at least 50% in the target language, and content (subject matter such as math, science, and social studies) should be taught in the target language. Learners receive all input in the target language and output in the target language is strongly encouraged. Traditional or formal L2 classrooms use both the L1 to explain structures and specific practice activities that help students learn specific language and interact with their peers. Learning in an at-home environment includes trying to immerse oneself in the target language at home and can include listening to radio, music, and TV; reading newspapers and popular magazines in the target language; and participating in social media. Study abroad involves learners in the target culture. Studies concerning the effects of AH learning contexts focused on the similarities and differences between immersion settings and the formal L2 classrooms in order to identify the factors influencing the efficiency of IM learning or FC learning. Immersion programs that were offered in AH environments were appealing to L2 instructors for the following reasons. First of all, participants of IM programs are exposed to the L2 for more hours than regular L2 classrooms. Specifically, more hours of formal instruction are provided in the IM contexts than formal classroom setting even if the years of IM programs (i.e., length but not intensity) is often shorter than foreign language programs in formal L2 classrooms. Furthermore, input is in the L2 and learners are encouraged to use only the

L2 and avoid using the L1 in the IM context. However, L2 learning is not limited to acquiring the language only; it also involves acquiring its culture. Immersion programs simulate an environment of using the L2 through a strong emphasis on learning content (subject matter) in the target language, but it is different from the target culture one gets in a natural setting. In contrast, study abroad (SA) programs combine immersion in the native speech community and formal classroom learning, thereby exposing learners to both the L2 and the culture shared by its users. There are some variations of the study abroad experience, as described by Freed (1995a):

> The terms "study or year abroad" are particularly American and European references. As a rule, study abroad programs combine language and/or content learning in a formal classroom setting along with immersion in the native speech community. Elsewhere similar experiences — which are sometimes reciprocal in nature — are termed "exchanges," as in the case of Australian students who study in Japan, Finnish students who study in Germany or England, or Canadian students who participate in interprovincial bilingual language learning programs. "Study abroad," an umbrella term to describe all these programs, may also refer to the experience of Peace Corps volunteers who receive intensive in-country language instruction prior to living and working in the community. (p. 5)

It is generally believed among students, teachers, parents and administrators that this integration of the target language and the culture creates the best environment for learning a second language and that students who go abroad will improve their L2 proficiency and ultimately become the most proficient users of their language of specialization (Freed, 1995b, p. 5).

In order to provide evidence supporting the linguistic benefits of SA, researchers have began to focus on assessing the effects of the SA experience. Some studies have been directed at a description of SA programs and their efficiency by presenting the performances of their participants (e.g., Guntermann, 1992a; Guntermann, 1992b; Isabelli, 2001, 2004; Llanes & Muñoz, 2009; Lord, 2009). An increasing number of studies turn to comparing SA programs with AH programs in terms of the linguistic performance in order to identify the advantages of a SA context (e.g., Collentine, 2004; Díaz-Campos, 2004, 2006; Segalowitz et al., 2004; Sunderman & Kroll, 2009). The latter research orientation is of particular interest for L2 researchers because participants of AH context (IM or regular classroom settings) can be used as a reference system or control group for the purpose of understanding and evaluating the effect of SA experience. For example, the Volume 26, Issue 02 of *Studies in Second Language Acquisition* (2004) was entirely devoted to studies on SA investigating the language learning and cognitive outcomes (no significant result for the latter) in two or more learning contexts (Collentine, 2004; Dewey, 2004; Díaz-Campos, 2004; Freed, Segalowitz, & Dewey, 2004; Lafford, 2004; Lazar, 2004; Segalowitz & Freed, 2004).

Research on the linguistic impact of SA experiences emerged during the 1980s, and this has been a relatively well-studied topic ever since (Segalowitz et al., 2004). Freed (1995b, 1998) made the most comprehensive view at that time of research on the effect of SA learning context. In her review (Freed, 1995a), evidence from studies with large samples generally demonstrates a positive effect of SA context. For example, based on the data from 2782 college seniors, Carroll (1967) reported that experience abroad was a predictor of proficiency. Dyson (1988) found that listening and speaking skills of 229 British students were improved considerably, especially for the lower proficiency student, after having studied in Spain, France, and Germany for 1 year. Similarly, Meara (1994) reported after analyzing self-reported data from 586 students that their oral skill had improved while they had studied abroad. Another large-scale study by Coleman, Grotjahn, Klein-Braley, and Raatz (1994) used 35,000 students from 100 institutions.

Results from this study indicated that growth in L2 slows down after returning from a year abroad immersed in the target language. In addition to large scaled quantitative studies, Freed also reviewed such case studies as Moehle (1984), Mohle and Raupach (1983), and Raupach (1984, 1987). These studies obtained consistent findings, such as improved global fluency and better compensation strategies (lengthening of sounds or discourse markers) after an SA experience.

Freed (1995b) also reviewed studies that used American Council on the Teaching of Foreign Languages (ACTFL) Oral Proficiency Interview (OPI) to test SA participants' oral proficiency development. Comparison of SA context with AH context indicates that SA students achieved higher score than students in the OPI performance. This result is confirmed by later studies using OPI (e.g., Freed et al., 2004; Segalowitz & Freed, 2004), which also found that SA participants outperform their AH counterparts in oral proficiency (e.g., faster rate of speech and less hesitation phenomena).

Although studies in general have produced positive results in favor of SA context, the validity of the data is challenged in terms of the measurement of language proficiency or research design. For example, some studies used a design without using comparative data or control groups in different contexts. Among all 12 empirical papers in the collection edited by Freed (1995b), only four compared SA data with AH data. Conclusions can be made too hastily without a strict control of extraneous variables, even if SA may be really effective. Others made claims about the advantages of SA generally based on students' anecdotal reports, holistic scale, or test scores, which provide limited information about the actual linguistic benefits of SA learning context because the benefits of SA context should not be limited to oral proficiency.

Recently, empirically findings on SA experience benefits have been expanded to linguistic skills other than oral proficiency. For example, Lafford and Collentine (2006) noticed that most comparative Spanish L2 studies have shown an advantage for the SA over the AH context in terms of oral proficiency, fluency, pronunciation, lexical development, narrative abilities, and discourse abilities. However, studies have yielded inconsistent or mixed findings. Again, in the collection of studies edited by Lafford and Collentine (2006), data in some studies failed to support the benefits of SA context; they found that classroom learners are equal to or even superior to SA learners in Spanish pragmatic abilities (Rodriguez, 2001), use of communication strategies (DeKeyser, 1991), and morphosyntactic and lexical development (Collentine, 2004; DeKeyser, 1991; Torres, 2003).

Concerning the effectiveness of classroom instruction in the SA context, findings were ambiguous. Some studies (e.g., L. Miller & Ginsberg, 1995) reported that participants held an ambivalent attitude or rejected the concurrent classroom instruction, while others (e.g., Brecht & Robinson, 1995) reported contrary findings that SA learners do generally value their concurrent classroom experiences. More attempts have been made to investigate the development of sociolinguistic competence and the effect of sociocultural factors on SA learners' gains. However, studies were unable to find rapid development of pragmatic competence (e.g., Hoffman-Hicks, 2002; Rodriguez, 2001). Other studies identified the negative effects of factors on the efficacy of the SA experience, like L1 discourse behaviors and sociocultural attitudes relating to gender and race within the target culture influence (e.g., Talburt & Stewart, 1999; Wilkinson, 1995).

In sum, previous studies have indicated the efficiency of the SA context. Its benefits are extended to linguistic and possibly nonlinguistic aspects, such as oral production, grammatical development, and lexical access. Nevertheless, a comprehensive understanding of the superiority of SA context involves taking many factors into consideration, such as variations in research design, length of stay, living conditions, testing instruments, the presence of classroom instruction, type of instruction, and pre-departure target language proficiency levels. Furthermore, there are other factors that may help promote an understanding of the effect of the SA learning context, for example, the way SA students spend their time, their dependence on L1 use, the frequency of target language use in their daily life, and their initiative in communicating with the target language community. Therefore, although SA students are often late bilinguals, they are likely to reach a high proficiency level.

Models of Bilingual Language Representation and Processing

One of the essential issues on bilingual language representation and processing is whether bilinguals share a single system of memory representation and processing for the two languages or whether each language has an independent systems (Kroll & Tokowicz, 2005). These concepts are critical to understanding the possible causes of cognitive advantage of bilingualism, and are discussed in this section. Among the early solutions was Weinreich's (1953) compound-coordinate representational model, which distinguished lexical and conceptual representations in bilingual memory organization. In the years that followed, a number of psycholinguistic models of bilingual representation and processing were developed as a result, and there was some empirical evidence supporting each alternative. These models include the Word Association Model (Potter, So, Eckardt, & Feldman, 1984), the Concept Mediation Model (Potter et al., 1984), the Revised Hierarchical Model (Kroll & Stewart, 1994), the Bilingual Single Network Model (Thomas, 1997), the Inhibition-Control Model (Green, 1986), the Bilingual Interactive Activation Model (Dijkstra & Van Heuven, 1998), the Bilingual Interactive Activation Plus Model (Dijkstra & Van Heuven, 2002), the Language Mode Framework (Grosjean, 1997), the Self-Organizing Model of Bilingual Processing (Li & Farkas, 2002), and the Bilingual Simple Recurrent Network Model (French & Jacquet, 2004), to name a few. These models either address the issues of whether the lexical representations of bilinguals' two languages are distinct or shared, how to account for the ways in which assumptions have been made about different levels of representation, or how to conceptualize language-processing tasks involving comprehension or production. This section provides an overview of the most commonly discussed models of bilingual representation and processing—models that separate L1 and L2 lexical representation, such as the Word Association Model, the Concept Mediation Model, the Revised Hierarchical Model, and models that focus on different levels of representation, such as the Bilingual Interactive Activation Model and the Bilingual Interactive Activation Plus Model.

The Word Association Model, the Concept Mediation Model, and the Revised Hierarchical Model

Earlier models of lexical representations assumed that a new L2 lexical representation is established and separated from the L1 lexical representation. Although early work seemed to support this assumption (e.g., Gekoski, 1980; Lambert, Havelka, &

Crosby, 1958), later research provided evidence against the idea of separate lexical representations (e.g., Chen & Ng, 1989; Kirsner, Smith, Lockhart, King, & Jain, 1984). The connections within and between the lexical and conceptual levels have been the topic of debate in the models on bilingual lexical processing, such as the Word Association Model (Potter et al., 1984) presented in Figure 2.1, the Concept Mediation Model (Potter et al., 1984) in Figure 2.2, and the Revised Hierarchical Model (Kroll & Stewart, 1994) in Figure 2.3.

As shown in Figures 2.1 and 2.2, these two models differ only in that the Word Association Model presented a direct link between L1 and L2 lexicon but no link between L2 and the conceptual stores, while the Concept Mediation Model held just the opposite assumptions. Compared with the two models proposed by Potter et al. (1984), the Revised Hierarchical Model shown in Figure 2.3 assumed links with each representation unit and made specific predictions about the link strength.

Table 2.2 provides a list of the proposed models of bilingual representation and processing and the empirical findings related to each model. The models in Table 2.2 are consistent with assumptions regarding the way in which concepts and linguistic elements from each language are represented in the bilingual mind. What is shared is that there is a single “storage space” for all the meanings of words and that there are two separate stores for each language lexicon. What differentiates the storage spaces from each other is the assumptions about the direction and strength of the links that connect these three memory stores. However, these theories of bilingual lexical representation and processing are based on behavioral evidence and have been criticized for three reasons: a) the question that the languages are functionally independent was ill-formed, b) the models proposed were underspecified, c) and the resulting evidence was difficult to interpret (Kroll & Tokowicz, 2005, p. 531).

The Bilingual Interactive Activation Model (BIA) and the Bilingual Interactive Activation Plus Model (BIA+)

BIA and BIA+ were developed to account for the ways in which assumptions have been made about different levels of lexical representation. The most extensively examined model has been the Bilingual Interactive Activation Model (BIA) first proposed by Grainger and Dijkstra (1992) and later revised by Dijkstra and Van Heuven (1998). This model is presented in Figure 2.4.

The BIA+ Model is concerned with the recognition of orthographic representations and allows for a precise simulation of the results from a series of experimental studies. It is based on the monolingual Interactive Activation Model (IA) by McClelland and Rumelhart (1981), in which processing is assumed to be activated by visual input from text and proceeds in a bottom-up manner from letter features to letters and to words. The IA is characterized by lateral inhibition (i.e., between nodes at the same level) as well as top down feedback (i.e., from nodes at a higher level downward). The BIA Model assumes an integrated lexicon for the two languages of a bilingual and consists of four representational levels: letter features, letters, words (their orthographic form), and language nodes. It is hypothesized that connections exist between the nodes within each level, as well as between the nodes of different levels. Activation or inhabitation of word units from letter units can take place, depending on whether there is a match or a mismatch with the input. In the case of a match, activation is sent by words to the corresponding language node and back to the letter level. A language node collects activation of all the words that belong to the corresponding language and sends inhibition to all the words belonging to the other language.

Many empirical studies have made successful simulations of the BIA Model (e.g., Dijkstra & Van Heuven, 1998; Grosjean, 1997; Van Heuven, Dijkstra, & Grainger, 1998), but others also indicate that some of the assumed mechanisms were wrongly illustrated and that some aspects of bilingual word recognition remain unexplained. Dijkstra and Van Heuven (2002, p. 181) evaluated the BIA Model and noticed the following limitations:

1. Phonological or semantic representations were not recognized in the BIA Model;
2. The representation of interlingual homographs and cognates is not fully specified;
3. Representational and functional aspects concerning language nodes were confusing;
4. A very limited account of how nonlinguistic and linguistic contexts affect bilingual word recognition was given;
5. Lack of detailed description of how participants perform a particular task; and
6. The relationship between word identification and task demands is not clearly accounted for.

Because of these limitations, the BIA model was updated by Dijkstra and Van Heuven (2002) to the BIA+ Model depicted in Figure 2.5. The new model, not limited to bilingual word recognition, has been extended to include phonologic and semantic lexical representations. Furthermore, it revised the role of language nodes and specified the purely bottom-up nature of bilingual language processing. This revision is supported by neuroimaging data linking this model to more neutrally inspired data that have a greater focus on the brain areas and mechanisms involved in comprehension and production tasks (Van Heuven & Dijkstra, 2010).

Table 2.3 is a summary and comparison of the two models discussed above, as well as the studies related to each model.

In addition to the use of behavioral evidence, neuroimaging technologies have also been employed over the past decade to examine bilingual representation and processing, although they have not been used so extensively as the behavioral approach. As a result, several factors influencing language representations in the bilingual brain have been identified. For example, Abutalebi, Cappa, and Perani (2005) reviewed dozens of studies addressing the cerebral representation of bilingualism and concluded that several factors may affect the neural basis of the bilingual language system. These factors include the age of L2 acquisition (AOA), the degree of proficiency for languages, and the degree of usage or the type and amount of exposure to the L2. Among these factors, proficiency has been shown empirically to be the most relevant factor because more extensive cerebral activations have been associated with production in the less-proficient language and vice versa.

It has also been shown that AOA may specifically affect the cortical representation of grammatical processing. Wartenburger et al. (2003) found that the brain activation pattern of the subjects in the late acquisition high proficiency category for the semantic task is roughly similar to that of subjects of early acquisition high proficiency. However, significant between-subject differences exist in brain activation during the grammatical task, which indicates the task-specific effect of age of acquisition. Exposure has been found to be an additional crucial factor for the neural representation of multiple languages. Data in Perani et al. (2003) indicate an effect of differential language exposure (measured by the frequency of daily language use, e.g., reading and socializing) on cerebral representations in multilinguals, even when the degree of proficiency is controlled. All in all, these factors affect brain activity, and they interact in a complex way with the levels of language representation and the modalities of language performance (Abutalebi et al., 2005, p. 512). Furthermore, new evidence from imaging studies has also suggested that the timing and context of L2 learning exert an impact on the organization of the two languages in the bilingual brain (Kroll & Tokowicz, 2005, p. 534). Accordingly, the researcher hopes that future neuroimaging studies will focus on clarifying the specificity and selectivity of interactions among these factors, as well as providing more information about how they interface with the levels of language representation. Advancements in research designs that provide a better fit for the empirical data, as well as access the validation of data through triangulation, have the potential to shed light on the puzzling results from previous studies.

Effect of Language Exposure on Adult L2 Learners

Two of the bilingual groups, the LH group and the LL group, used in this study are sequential/late bilinguals, and some of them started learning an L2 after puberty or in adulthood. These two groups included individuals with varying language learning experiences. Some were returned missionaries, some had study abroad experiences, and others were traditional classroom L2 learners (see Chapter 3 for detailed description of the three groups). Other than language proficiency and learning context (which differs in the intensity, manner of language input, and amount of language usage), the AOA is an important difference between the sequential/late bilinguals and the simultaneous/early bilinguals. Child language acquisition is a well-studied topic (e.g., Akhtar & Menjivar, 2012; Benavides-Varela, Hochmann, Macagno, Nespor, & Mehler, 2012; Gervain & Mehler, 2010), compared with the mechanism of adult SLA, and this section will review studies on the effect of L2 exposure on the adult learner's brain.

It is generally recognized that the age is a factor working against native-like attainment in adult SLA (Birdsong, 2006). Nevertheless, the adult leaner's brain is plastic enough to adapt to new language input, as an estimated 5% to 15% of adult learners can achieve native-like performance (Birdsong, 1999). Flege and Liu (2001) concluded in their study on Chinese immigrants in the US that "Evidence that age (or neurological development) constrains L2 learning should be considered persuasive only if it can be shown that the participants under examination had received the kind of rich input that is needed for successful L2 learning" (p. 550).

Studies over the past 2 decades have consistently found that language input shaped through interaction contributes directly and powerfully to acquisition (Long, 1981) and that social interaction (Conboy, Brooks, Meltzoff, & Kuhl, 2008; Conboy & Kuhl, 2007; Kuhl, 2007; Kuhl et al., 2008; Kuhl, Tsao, & Liu, 2003) and continued language exposure (Flege, Yeni-Komshian, & Liu, 1999; Pallier et al., 2003) are vital for successful language acquisition. For instance, behavior research on first language attrition in sequential bilinguals implies that the maintenance of native-like proficiency requires sustained language exposure throughout the "critical period" and possibly beyond (Schmid & Dusseldorp, 2010; Schmid & Köpke, 2007, 2008), and this view is confirmed by imaging data on subtractive bilinguals whose L1 input was abruptly replaced by L2 input.

Pallier et al. (2003) raised the question of whether one's first language can be completely replaced by a second language that is acquired later in life. They conducted both behavior and event-related fMRI studies on eight adult subjects (20 to 32 in age) who were born in Korea and adopted by French families between the ages of 3 and 8. All of them were native speakers of Korean before their adoptions and subsequently became native speakers of French and claimed no memory of Korean. Behaviorally, when tested on knowledge of this language, there is no significant difference between their performance and native French controls who had never been exposed to Korean, i.e., the adoptees were unable to distinguish Korean from other languages at both word and sentence level. In addition, fMRI data showed that their brain responded the same way to auditory stimuli in Korean, as well as unknown languages. Compared with native French controls, the adoptees exhibit similar, but broader brain activation when listening to French, their adopted L1. This study indicates that even by 8 years of age, the brain is still plastic enough to allow the newly acquired language to gradually replace one's first language. It is also evidence that continued language exposure beyond childhood is necessary to maintain first language representation in the brain.

In infant brains, both natural maturation and first language exposure are important in shaping the language circuitry (see Friederici, 2005; Kuhl, 2004 for reviews). Although the adult brain is comparatively less plastic, it is still sensitive enough to be reshaped by exposure to a second language (Ellis & Sagarra, 2010; Rast, 2010). Table 2.4 contains a list of imaging studies focusing on how the adult brain responds to L2 language input.

The studies in Table 2.4 suggest that, like infant brains, the adult brain is capable of extracting statistical information from a newly encountered language and that even a short amount of exposure to a new language could produce observable changes in neural networks. These studies investigating the cognitive mechanisms underlying the initial stages of adult L2 learning (see Rodríguez-Fornells, Cunillera, Mestres-Missé, & de Diego-Balaguer, 2009 for a summary on brain mechanisms involved in adult language learning) are evidence of adult brain plasticity, but as suggested by Davidson (2006), it is necessary to employ longitudinal studies to identify predictors of later performance and understand individual difference in learning outcomes. There are many ways adult L2 learning differs from simultaneous bilinguals acquiring languages in bilingual environments at an early age. For one thing, adults already possess a well-established L1 network in the brain, and the new language input cannot be processed entirely in the same manner as infants or children, not to mention the differences in the nature and amount of the input received during the learning process. Over time, such differences (e.g., AOA, language leaning context) are likely to bring structural changes in the brains, and manifest as behavior variations in cognitive control, as language and cognition are closely related to each other.

Bilingualism and Cognitive Control

Traditionally, theoretical linguists assume that the human brain is hardwired with a limited set of rules for generating language, known as Universal Grammar (UG), and that the faculty of language is separate from other cognitive abilities (Chomsky, 2007). This modular approach on language and cognition remains a strong influence on theories of language acquisition in general. Neuroimaging research on language over the past 2 decades, however, points to the fact that the representation and processing of language involves shared neural networks with domain general cognitive functions such as attention and working memory (for reviews on roles of attentional control and working memory, see de Diego-Balaguer & Lopez-Barroso, 2010 and Rodriguez-Fornells, De Diego Balaguer, & Münte, 2006), and different language systems are interconnected (for discussion on differences between L1and L2 processing, see Indefrey, 2006 and Stowe, 2006).

The brain has a limited volume; however, there are almost an unlimited number of cognitive skills in its repertoire. Therefore, a modular perspective (i.e., the brain is seen as being primarily composed of innate neural structures or modules that have distinct and established evolutionarily developed functions) on cognitive functioning is neither energy efficient or practical. In other words, various cognitive functioning has to make use of overlapping neural networks and similar neural networks may underlie functions in different mental domains that also include language. For example, Price (2010) concluded in her review of fMRI studies on language that the original "syntax area" Brodman's Area (BA) 47 is, in fact, involved in sequencing both linguistic and nonlinguistic events. From an evolutionary perspective, language control shares similar networks (e.g., Broca's area or inferior frontal gyrus, to be more precise) with action control (Green & Abutalebi, 2013; Stout & Chaminade, 2012), regardless of language status (bilinguals or monolinguals).

Evidence of this over-lapping network comes from studies on bilingualism and cognitive control. There are a number of advantages to bilingualism in terms of cognitive control. Current research has recognized that acquiring a second language can not only enhance linguistic abilities, such as metacognitive awareness (i.e., one's ability to think about one's own learning process), but also can produce positive transfer to nonlinguistic cognitive processing, such as better performances in tasks involving interference control, cognitive flexibility, and theory of mind (TOM) (i.e., the ability to understand intentional states, such as beliefs and desires, in others). Although it is not the focus of the current study, it is important to mention that acquiring a second language can also protect against the cognitive decline that comes with aging (for reviews, see Bialystok, 2009, 2011; Bialystok, Craik, Green, & Gollan, 2009).

The most likely cause of such advantages could be due to the fact that in the bilingual brain, both languages are constantly active and competing for attentional resources; therefore, bilinguals often have to switch on one language mode while inhibiting another, even in monolingual contexts (e.g., Linck et al., 2009). This practice, which could be lifelong for simultaneous bilinguals, strengthens the general attentional control network and contributes to the cognitive flexibility in bilinguals. This position is confirmed by Abutalebi (2008), who concluded in his review of imaging studies on language that similar neural substrates underlie L2 and L1 acquisition and that bilingual code-switching is a matter of prefrontal selection or inhibition of the network. The position is also echoed in Green and Abutalebi's (2013) adaptive control hypothesis.

Early studies on cognitive control in bilinguals used the dimensional change card sorting task (Bialystok, 2003; Bialystok & Martin, 2004) to assess executive functions. The studies published after 2004 employed a number of cognitive tasks, such as the Stroop, the Simon task, the spatial Simon task, Flanker task, and Attention Network Task (ANT) (for task reviews, see Green & Abutalebi, 2013; Hilchey & Klein, 2011).

However, studies using the same or similar tasks differ in the number of trials and the ratio of conditions (see Bialystok, 2006; Bialystok, Craik, & Luk, 2008; Bialystok & Senman, 2004; Carlson & Meltzoff, 2008; Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009; Costa, Hernández, & Sebastián-Gallés, 2008 for example). This inconsistency in the instruments measuring cognitive control could be one reason for the lack of consistent results. Table 2.5 lists some of the most recent studies on cognitive control in bilinguals along with the methods used and the results.

As shown in Table 2.5, the most common behavior findings along this line of research is that bilingual children and older adults are often faster in completing interference control tasks than monolinguals, but this finding is often absent in bilingual young adults or could only be observed in the beginning of the experiments (see Hilchey & Klein, 2011, p. 654). The most prevalent hypothesis accounting for the inconsistencies has been that this result could reflect a strategy or processing difference between bilinguals and monolinguals that is only discernible in the initial sessions of the task, and this is supported by distinct activation patterns in imaging studies (e.g., Luk et al., 2010). However, the findings could also be explained by the fact that any processing advantages in bilinguals were made up by monolinguals through recruiting additional brain networks, as unlike children or older adults, young adults were at the prime of their cognitive control and have more cognitive reserve available. In other words, the same task performance result is achieved at different costs for the two groups, monolinguals are mobilizing more attentional control resources to catch up with bilinguals. If this is the case, then behavior result differences between these two groups could emerge when the experiment task is made more challenging, so that monolinguals are no longer able to keep pace with bilinguals.

In the current study, the Simon task instructions were read to the participants and shown on computer screens at the beginning of each task session (see Chapter 3 for task descriptions). The task instructions added an emphasis of staying on task by reminding the participants to pay attention to the direction of the arrow, not its physical space location, and warning them about possible distractor trials. Previous studies (Kane & Engle, 2003; A. E. Miller, 2014) found that people with high attentional control capacity were likely to strategically withhold cognitive control in order to reserve limited attentional resources, and their performance in the standard Simon task could suffer from insufficient allocation of attention. This modification in task instruction was found to encourage exertion of cognitive control in participants. Assuming AOA and L2 proficiency would result in cognitive processing differences among the three groups of bilinguals, the experimental change mentioned above should make the possible cognitive processing advantages manifest in behavior studies.

As listed in Table 2.5, the majority of studies on bilingual cognitive control compares two groups, i.e., a simultaneous bilingual group (sometimes an early immersion group was used instead) vs. a monolingual control group (see Hilchey & Klein, 2011, pp. 630-631 for details). The sequential/late bilinguals, especially those low in language proficiency, are not considered proficient or active second language users and are often excluded in studies on the cognitive benefits of bilingualism (e.g., Luk, De Sa, & Bialystok, 2011). Yet, the 2007 American Community Survey found that only 20% of Americans were possibly simultaneous bilinguals (Shin & Kominski, 2010). The sequential bilinguals were often part of studies that compare returned study abroad students and classroom L2 learners to investigate the cognitive and language learning outcomes of immersion (e.g., Linck et al., 2008; Linck et al., 2009; Sunderman & Kroll, 2009), but these studies sometimes reported findings that contradicted previous studies. Therefore, the present study adopted a cross-sectional design by including two groups of late bilinguals and comparing them with an early bilingual group, relative to their language proficiency and executive functioning. Such a comparison makes it possible to look into whether or not better cognitive control can also be found in late bilinguals, and whether or not enhanced executive functioning is correlated with AOA and L2 proficiency or simply with innate working memory (WM) capacity, which is an indicator of both verbal WM capacity and language aptitude (Daneman & Merikle, 1996). In this paper, I use the term *working memory* to refer to a hypothetical cognitive system that has limited capacity and is responsible for providing access to information required for ongoing cognitive processes. I use *working-memory capacity* (WMC) to refer to an individual differences construct that reflects the limited **capacity** of a person's **working memory**. Three lab tasks were used in the current research. A verbal WM task, the reading span task, was included in the experiment design to measure possible WM differences in these three groups of bilinguals. Two additional cognitive tasks (see Chapter 3 for task descriptions) in this study were the stop-signal paradigm (Verbruggen, Logan, & Stevens, 2008), which measured response inhibition, and the Simon task (Simon, 1969), which measured interference control. These three tasks provided good assessment of the overlapping cognitive control network.

Research Questions and Hypotheses

The present study examines the differences among an early bilingual group and two late bilingual groups relative to their language proficiency and executive functioning. The following research questions are addressed:

1. Do these three groups differ in WM capacity, as measured by the reading span task?
2. Are there significant differences in the three groups of students' performance on stop-signal paradigm, which measures response inhibition?
3. After dividing students into high and low span groups based on their Reading Span score, are there significant differences in their performance on stop-signal paradigm and the Simon task?
4. What are the relationships among the dependent variables (RTs and Accuracy) in the stop-signal paradigm?
5. Are there significant differences among the three groups of students in their performance on the Simon task?
6. What are the relationships among the dependent variables (RTs and Accuracy) in the Simon task?
7. Can WM capacity predict performances in the stop-signal paradigm and the Simon task?

Hypotheses

Based on previous literature, this study puts forward the following hypotheses:

1. There is no significant difference among the three groups on their reading span task performances.

2. The simultaneous bilingual group outperforms the other two groups on the Simon task and the stop-signal paradigm, followed by the LH group.
3. The high span group outperforms the low span group on the Simon task and the stop-signal paradigm.
4. For the stop-signal paradigm and the Simon task, accuracy reduces as a result of spending less time making responses, i.e., faster RT.
5. Both foreign language proficiency and WMC contribute to above-mentioned outcomes, but the latter should have a larger effect.

To sum up, the current study investigated the effect of foreign language learning on cognitive control. Specifically, WMC will be measured through the reading span task, and cognitive control (i.e., interference suppression and response inhibition) will be measured through the Simon task and the stop-signal paradigm. The design of the current study improves on previous instruments used to assess cognitive control (for details, see Chapter 3). The inclusion of two sequential/late bilingual groups in the research design will provide information regarding the effects of age of onset and foreign language proficiency on cognitive control development.

Table 2.1

Classification of Bilinguals

Criteria	Types of Bilinguals
Relationship between language proficiencies in two languages	Balanced and dominant bilinguals
Age of acquisition	Simultaneous, sequential, and late bilinguals
Functional ability	Receptive and productive bilinguals
Organization of linguistic codes and meaning units	Compound, coordinate, and subordinate bilinguals
Language status and learning environments	Elite/elective and folk/circumstantial bilinguals
Effects of L2 learning on the retention of L1	Additive and subtractive bilinguals

Table 2.2

Summary of Models on Bilingual Lexical Processing

Researchers	Models	Propositions	Empirical Results
Potter et al. (1984)	The Word Association Model	The model proposes that a direct link exists between a bilingual's first language and his or her second language at the lexical level, and that only L1 is directly associated to the underlying conceptual store. In second language acquisition, that link is employed to understand and produce words in L2 by retrieving a word in L1. Accordingly, an access to the meaning of an L2 word is achieved through the translation of that word into the corresponding L1 word lexically, followed by retrieving of its meaning out of the conceptual store.	Support for this hypothesis from Scarborough et al. (1984). No evidence for a direct association between words in the two languages (Potter et al., 1984); Evidence from novice bilinguals (Kroll & Curley, 1988)
Potter et al. (1984)	The Concept Mediation Model	No direct links exist between L1 and L2 at the lexical level; both L1 and L2 lexical stores have direct access to a shared conceptual store or semantic representation, which mediates the cross-language priming effect.	Evidence for the links between both L1 and L2 and a shared conceptual store without the help of a direct association between L1 and L2 lexical store (Potter et al., 1984).
Kroll & Stewart (1994)	The Revised Hierarchical Model	It includes three stores: in the first and second stores, L1 and L2 lexical stores in which lexical information of both is organized; in the third store (conceptual), conceptual or meaning information common to both languages is stored. The strength and use of links between the lexical stores and the conceptual stores are determined by the	Evidence supporting the asymmetrical hypothesis of RHM is from the studies by Kroll & Stewart (1994) and Sholl et al. (1995). Previous studies do not support the asymmetrical hypothesis (Heij, Hooglander, Kerling,

Table 2.2 continued

Researchers	Models	Propositions	Empirical Results
		direction of translation. Accordingly, links from L1 to L1 lexical items are stronger than links from L1 to L2, and L1 words have stronger links to concepts than l2 words at the conceptual level.	& Van Der Velden, 1996), contradict the hypothesis (De Groot & Poot, 1997; Duyck & Brysbaert, 2004), or obtain mixed results (Hatzidaki & Pothos, 2008).

Table 2.3

The BIA Model and the BIA + Model

Researchers	Models	Propositions	Empirical Results
Grainger & Dijkstra (1992); Dijkstra & Van Heuven (1998)	The BIA Model	• Resting level activation of words reflects the state of language activation as well as proficiency; • Stimulus list composition (previous items) affects activation state of word forms; • Participant expectations do not exert strong effects on the activation state of words; • Top-down inhibition effects on the nontarget language arise via language nodes; • Identification and decision levels interact (Dijkstra & Van Heuven, 1998)	Successful simulations by the BIA Model (Dijkstra & Van Heuven, 2002; Grainger & Dijkstra, 1992; Grosjean, 1997)
Dijkstra & Van Heuven (2002)	The BIA+ Model	• Resting-level activation of words reflects the state of language activation as well as proficiency • Stimulus list composition (previous items) affects task/decision system • Participant expectations may affect task/decision system • No top-down effects from task/decision system on identification system (bottom-up activation of words) • Identification–decision: purely bottom-up information flow • Nonlinguistic context affects task/decision system, while linguistic context affects activation of words (Dijkstra & Van Heuven, 2002)	Neuroimaging studies support many of the assumptions of the BIA+ Model, while more research is needed to fully specify the neural correlates of BIA+ (Lam & Dijkstra, 2010; Van Heuven & Dijkstra, 2010).

Table 2.4

Imaging Studies on the Effect of L2 Exposure on Adult Learners

Authors	Related questions	Methods	Participants	Relevant findings
Osterhout et al. (2006)	The amount of L2 exposure needed for L2 knowledge to be incorporated into learners' online comprehension processes	Longitudinal ERP studies after 14 hrs., 60 hrs., 140 hrs. of formal classroom instruction	14 English-speaking novice French learners (college students)	Incorporation of different aspects of L2 knowledge followed a timeline, and that certain aspects of L2 knowledge (e.g., lexical and morphosyntactic aspects) could be implemented rapidly following short periods of exposure
Gullberg et al. (2010)	The effect of amount of exposure on word recognition after 7 and 14 mins of continuous audiovisual input	Behavior tests; fMRI study on functional connectivity of regions involved in word learning during resting periods of 5 minutes before, between, and after two sessions	Adult Dutch-speaking novice Chinese learners (number not reported)	The supramarginal gyri only showed connectivity differences between learners and nonlearners after exposure. For all learners, left insula and Rolandic operculum as well as left SMA and precentral gyrus showed stronger connectivity only before exposure
Davidson (2010)	Review recent work on certain electrophysiological correlates of grammar learning	EEG, ERP, MEG	Adults	Individual variability in cingulate and medial prefrontal function is related to final proficiency
McLaughlin et al. (2010)	How and when learners incorporate L2 knowledge into their online language processing system	Review ERP studies investigating the neural correlates of L2 grammatical learning	Novice adult learners progressing through their first year of L2 classroom instruction	Some learners progress through discrete stages of grammatical learning during the first year of instruction. The variability in learners' brain response is highly systematic and can be used to differentiate learners

Table 2.4 continued

Authors	Related questions	Methods	Participants	Relevant findings
Schlegel, Rudelson, & Tse (2012)	The role of structural plasticity in long-term learning process of foreign language acquisition	Monthly DTI scans .	11 English speakers who took a 9-month intensive course in written and spoken Chinese vs. 16 controls who did not study the language (mean age= 20.05)	Language learners exhibited progressive changes in white matter tracts associated with traditional left hemisphere language areas and their right hemisphere analogs, with the most significant changes occurred in frontal lobe tracts crossing the genu of the corpus callosum
Morgan-Short, Steinhauer, Sanz, & Ullman (2011)	Whether explicit training and implicit training differentially affect neural and behavioral measures of syntactic processing of an artificial language	ERPs after training	30 Adults (mean age= 24), 14 in implicit training (that approximates immersion settings) group, and 16 in explicit training (that approximates traditional grammar-focused classroom settings) group	Although performance of explicitly and implicitly trained groups did not differ at either low or high proficiency, only implicitly trained group (high proficiency) exhibited an electrophysiological signature typical of native speakers

Table 2.5

Recent Studies, Methods, and Results of Studies on Cognitive Control in Bilinguals
(M = monolinguals, B = bilinguals)

Study	Participants	Mean age	Task	Results
Gregory J Poarch & van Hell (2012)	L1= German M = 20, B =18, L2 learners of English=19. Trilinguals (L3 either German or English) = 18. All except M were enrolled in immersion programs	M = 7.1, B = 6.8, L2 learners of English= 6.9, trilinguals (T) = 6.8.	Simon task ANT	No significant difference in global RTs. No significant difference in Simon effect between L2 learners and M, B and T, M and B (p = .062). For ANT (M were excluded), no significant difference in global RTs. B and T did not differ in orienting and conflict resolution effects. B showed a significantly greater orienting effect than L2 learners, but the difference between T and L2 is not significant (p = .067). Both B and T displayed enhanced conflict resolution.
Luk, Anderson, Craik, Grady, & Bialystok (2010)	9 in each group. L2 includes heterogeneous non-English languages.	M = 20 B = 22	Flanker task (480 trials), with an even distribution of congruent, incongruent, no-go, neutral, and baseline trials	There was similar RT between groups. fMRI revealed distinct activation pattern for congruent and incongruent trials but similar patterns for no-go trials. Both groups showed increased activation to suppress interference from incongruent flankers. The networks associated with more efficient interference suppression were different in each group.

Table 2.5 continued

Study	Participants	Mean age	Task	Results
Bialystok (2010)	M = 25, B = 26. L2 includes heterogeneous non-English languages.	M = 6.1 B = 6.0	trail-making task, global–local task (16 blocks with 12 trials in each; the ratio of congruent, incongruent, and neutral trials were not reported)	Bilinguals completed all tasks faster than monolinguals
Martin-Rhee & Bialystok (2008)	Study 1: 17 in each group Study 2: M = 20, B = 21 (heterogeneous non-English languages spoken at home) Study 3: M = 19, B = 13. Both M and B received 2 hrs. of Hebrew classes per day.	Study 1: M = 4;7, B = 5 Study 2: M = 4;5, B = 4;6 Study 3: mean age of 8;0	Study 1: three versions of Simon task (immediate, short delay, long delay) Study 2: Simon task, day-night Stroop task Study 3: univalent and bivalent arrows task (I think the second one is the spatial Simon task)	Study 1: No difference in Simon effect. Faster RTs for B only found in the immediate task. Study 2: Faster RTs for B only found in the Simon task. No difference in other measures. Study 3: Faster RTs for B only found in the Spatial Simon task. No difference in other measures.

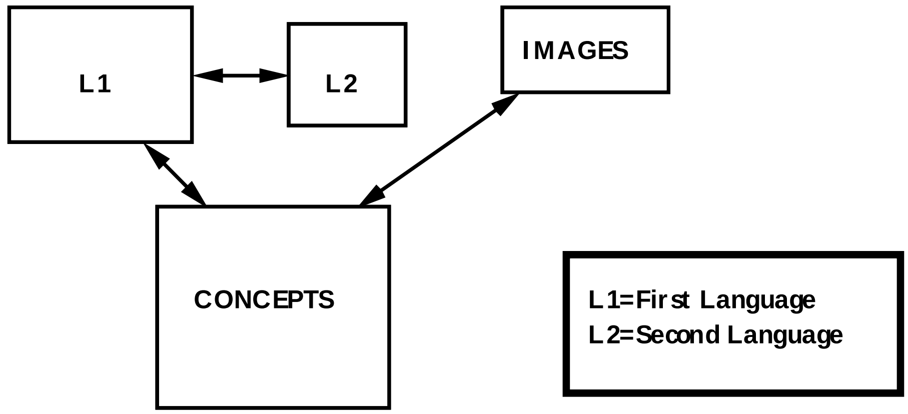

Figure 2.1 The Word Association Model Adapted from Potter et al. (1984)

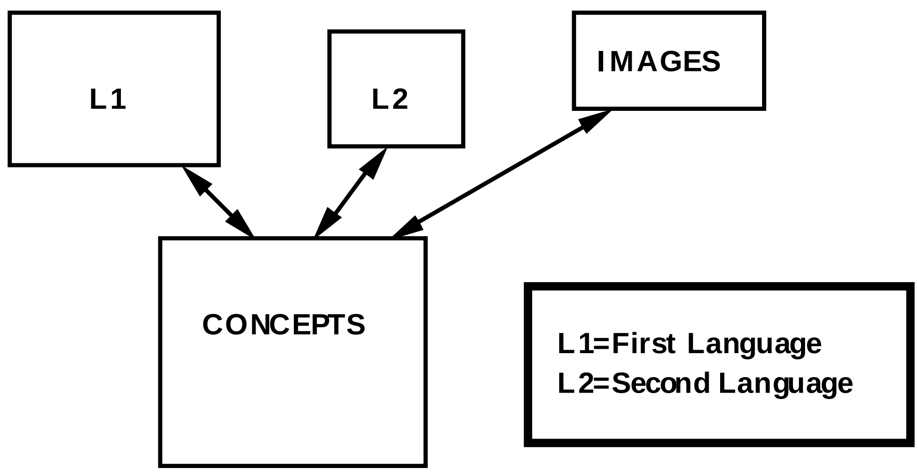

Figure 2.2 The Concept Mediation Model Adapted from Potter et al. (1984)

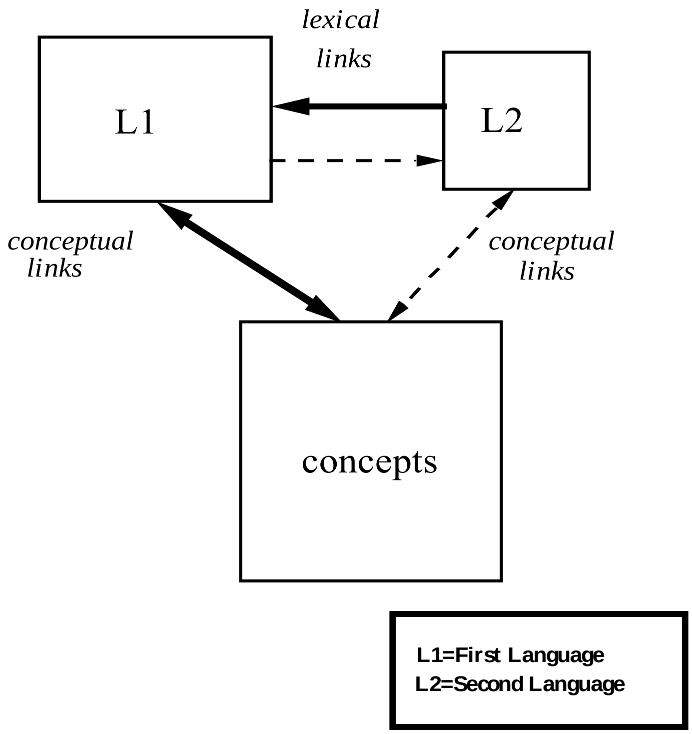

Figure 2.3 The Revised Hierarchical Model Adapted from Kroll and Stewart (1994)

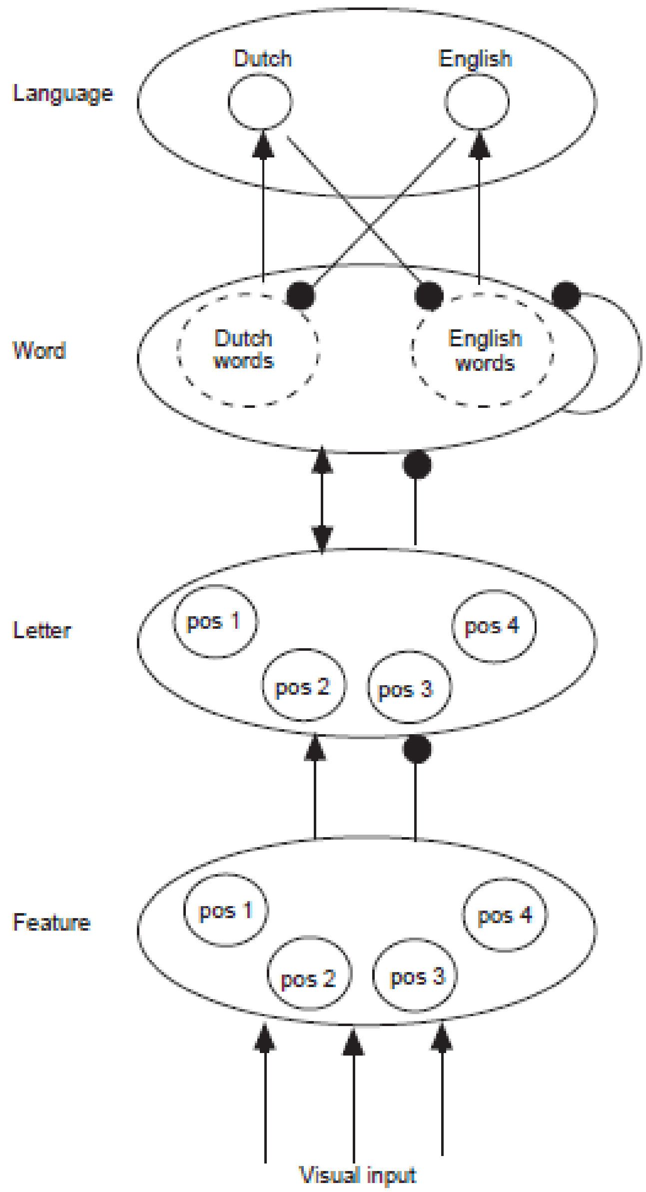

Figure 2.4 The BIA Model Adapted from Dijkstra and Van Heuven (1998)

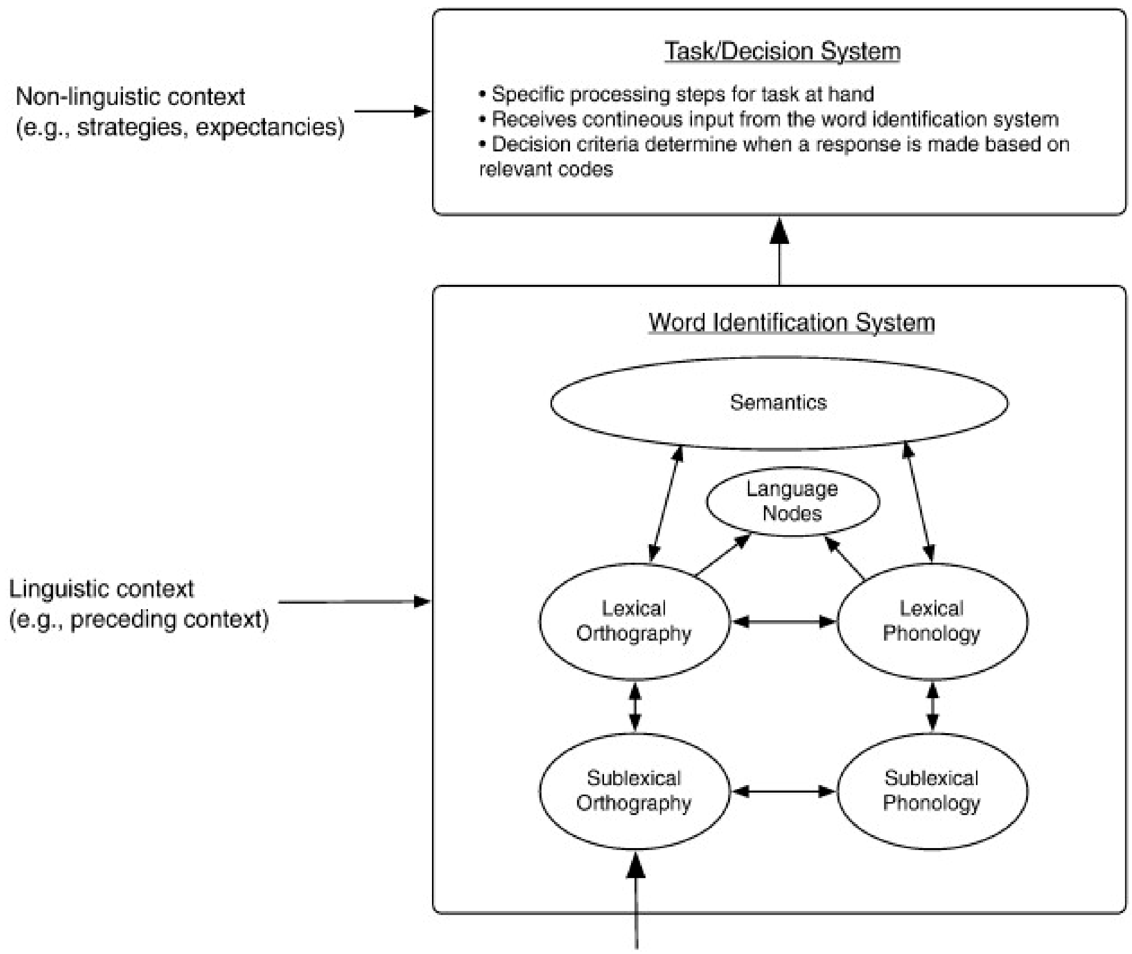

Figure 2.5 The BIA+ Model Adapted from Dijkstra and Van Heuven (2002)

CHAPTER 3

METHODS

The aim of the present study is to explore the joint effects of ultimate language proficiency and age of acquisition (AOA) on cognitive control. The study adds to the existing body of literature on bilingualism by incorporating two sequential bilingual groups (i.e., a late high proficiency bilingual group and a late low proficiency bilingual group) that are the most common in the United States, and by using a cross-sectional design to investigate the cognitive processing differences among the two late bilingual groups and one early/simultaneous bilingual group. Such a comparison makes it possible to look into whether or not sequential bilinguals enjoy the same cognitive benefits over monolinguals as simultaneous bilinguals, and whether or not this cognitive processing advantage is correlated with the ultimate language proficiency or AOA. In other words, we want to know if starting to learn a new language before age 3 (while the brain is considered to be quite plastic) is a required condition for the early bilingual edge that has been observed in previous studies (for reviews, see Akhtar & Menjivar, 2012; Bialystok & Craik, 2010).

Participants

Participants were 181 undergraduate students recruited from the University of Utah and two nearby colleges. There were 108 females and 73 males. Their age ranged from 18 to 35 years (*M* = 22.97, *SD* = 3.54). Participants fell into three groups determined on the basis of their AOA and foreign language proficiency: early bilinguals (*n* = 57), late high proficiency bilinguals (*n* = 80), and late low proficiency bilinguals (*n* = 44). All participants are fluent speakers of English and right-handed, with normal hearing and normal or corrected-to-normal vision. Participants were compensated with either $20 or course credits for participating in this study. Participants were provided with written informed consent prior to participation and a written debriefing before they left. The language learning profile of the three groups is presented below.

The early bilinguals (EB) were exposed to at least two languages (e.g., English, Spanish, Chinese, Japanese, Persian, etc.) before the age of 3 and are fluent users of both languages. In this group, 19.3% served a full time LDS mission (*n* = 11); 15.8% took part in study abroad programs of varying lengths (*n* = 9); 54.4% had the experience of traveling abroad (*n* = 31).

There are two groups of sequential/late bilinguals. The late high proficiency bilingual group (LH) consists of students who started learning a new language after aged 5 and self-rated their language proficiency (speaking or writing) to be “4” or “5” on a 1 to 5 Likert scale with “1” being the lowest level of proficiency and “5” being the highest. Most of the participants in this group had the experience of traveling abroad (62.5%, *n* = 50) or studying abroad (35%, *n* = 28). Close to half of the group (47.5%, *n* = 38) consists of returned, full-time missionaries (2 years for men and 18 months for women) for the

Church of Jesus Christ of Latter-Day Saints (LDS), also known as the Mormons. The latter is a sample of convenience in Utah because it is common for Mormon families to send their age-appropriate children abroad to serve full-time as missionaries. The minimum age for serving a mission is aged 18 for young men and aged 19 for young women. Before serving a mission outside of the United States, or in areas where a language other than English is widely spoke, potential missionaries undergo intensive foreign language training for eight to 13 weeks (depending on the target language) at the Missionary Training Center (MTC) adjacent to the Brigham Young University campus or in one of the 15 MTCs around the world. Sometimes the missionaries receive the language-training portion of their missionary training abroad if the country in which they will serve their mission has an MTC.

The MTC pedagogy is immersion, with students studying 6 to 8 hours per day in class and immersing themselves in the target language at other times, such as during lunch, dinner, and break times. The LDS church has detailed rules concerning missionaries' duties and daily life schedules, and most missionaries became fluent speakers (but may have many grammatical errors and limited vocabulary) of the target languages by the time their missions come to an end. From a language learning perspective, the missionary experience is similar to that of a long-term study abroad program in which students have to earn college credits in a foreign country.

The late low proficiency bilingual group (LL) consists of students who started learning a new language after age 5 and also self-rated their language proficiency (i.e., speaking or writing) to be 3 or under on a 1 to 5 Likert scale. Among this group, 9.1% participated in study abroad programs (n = 4), and 29.5% travelled abroad (n = 13).

None of them served an LDS mission that required the frequent use of a foreign language.

Procedures

Experiments were conducted in the computer lab in the Department of Linguistics. Participants completed three tasks in the following order: Reading Span, Stop-Signal Paradigm, and Simon Task. All tasks were conducted in English. A 5-minute break was given between each task, and participants were free to take longer breaks if requested. At the end of the experiment, participants were asked to complete an online questionnaire about their language background, proficiency level, and language learning experiences (see Appendix A). The entire experiment session for each participant took less than 2 hours.

Tasks

Reading Span Task

This study used an automated dual-task version for measuring working memory capacity (cf., Unsworth, Heitz, Schrock, & Engle, 2005). Participants were instructed to make semantic judgments on a series of unrelated sentences (e.g., a sentence like “Mr. Jones asked his son to water the cats and mow the lawn.” would be “False”). Immediately after each sentence, a random letter is to be memorized. After completing varying numbers of sentence-letter pairs (from three to seven pairs) in a set, participants were prompted to recall all letters in the order presented. The final score (absolute score), which ranged from 0 to 75, was calculated by adding together the values of all sets in which the letters were recalled in the correct sequence. Participants were instructed to keep the sentence judgment accuracy at 85% or higher, so as to ensure that they paid attention to both tasks. Those participants who made 15 or more reading errors were excluded from subsequent analyses.

Stop−Signal Paradigm

This task measures response inhibition by using a primary task and an auditory cue (Verbruggen et al., 2008). The primary task was to respond to the shape of each stimulus presented centrally on a computer screen, by either pressing the “Z” key on the left when square appeared or the “/” key on the right when circle appeared. On go trials (75% of total trials), only the primary task stimulus (shapes) was presented. On stop-signal trials (25% of total trials), an auditory cue (a tone) followed the presentation of the shapes. Participants were instructed to withhold their response (by not pressing any key) for that trial as soon as they heard the sound. These two trial conditions were randomly presented in this task.

In stop-signal trials, the time between the onset of the shapes and the onset of the auditory stop-signal/ tone is known as stop-signal delay (SSD), which would vary on the basis of participant performance. When one stop-signal trial was successfully inhibited, the SSD would be increased by 50 milliseconds (ms) in the next stop-signal trial. A stop−signal trial that was not successfully inhibited (i.e., by key-pressing) would result in the SSD being decreased by 50 ms in the coming stop-signal trial.

Participants were instructed to respond as quickly and accurately as possible. They were provided with a practice session of 32 trials, followed by three blocks of 64 trials. There was a 10-second automatic break after each block, when performance feedback on the previous block was presented, including the number of incorrect responses on no−signal trials, the number of missed responses on no-signal trials, the mean RT on no-signal trials (NS-RT), and the percentage of correctly suppressed trials.

The stop-signal reaction time (SSRT), which indicates how long it takes a person to suppress their ‘go’ response upon the presentation of the auditory stop-signal, is calculated by subtracting the mean SSD from mean primary task RT (Logan, Schachar, & Tannock, 1997). Participants with a *p*-value of 0 were excluded from further analysis due to failure of attending to the primary task.

Simon Task

Interference suppression was measured by Simon task. The variant used for this study is also known as the Spatial Stroop or the Arrow Judgment task (for a review, see Hommel, 2011). Participants were instructed to push the “Q” key on the keypad with their left hand when they saw a left facing arrow (e.g.,←) and push the “P” key with their right hand for a right facing arrow (e.g.,→). Arrows were presented for an orientation judgment in two different conditions: congruent (75%) and incongruent (25%). In the congruent condition, arrows were presented on the same side of space as they are facing (i.e., a left-facing arrow presented in the far left side of space approximately 5 degrees from a central fixation area). In the incongruent condition, arrows were presented on the opposite side of space as they are facing (i.e., a left-facing arrow presented in the far right side of space). With the conflict in arrow direction and spatial position, the incongruent trials required the participants to overcome the drive to respond to spatial location only, a strategy that would work well for the congruent trials. The high-congruency proportion was adopted because Kane and Engle (2003) reported that such a ratio makes participants rely on the most salient feature of the stimulus, arrow position, thus increasing the conflict when encountering incongruent trials. This task had three sessions (800 trials each) and a 5-minute break was given between each session. RT and accuracy in congruent and incongruent trials, and the size of Simon effect, which is the RT differences between congruent and incongruent trials, were calculated and compared across the three groups. Trials with RTs <200ms or >1500ms were excluded from all analyses.

For the Simon task version used in this study, the following instructions were read to the participants at the beginning of each session:

> In this experiment you will be presented with an arrow pointing to either the left or right on the computer screen. The arrow could appear on the left half or right half or center of the screen. Please ignore the location of the arrow and simply respond based on the direction of the arrow by pressing a key on either the left or right side of the keyboard corresponding to the direction of the arrow. If the direction of the arrow is left, press the ″q″ key. If the direction of the arrow is right, press the ″p″ key.
>
> You may find on many of the trials the arrow direction and the arrow location are the same, making it easy to respond to the spatial location of the arrow. But these are distracter trials that make you reliant on the spatial location.
>
> Remember this is not the task instruction and may cause you to perform poorly on the trials we are most interested in where the spatial location and arrow direction differ. For that reason, it is extremely important that you ALWAYS ignore the spatial location of the arrow and focus instead on the direction the arrow is pointing.
>
> Please respond as quickly and accurately as possible.

Questionnaire

The online questionnaire had 22 possible questions and was designed to collect information on participants' language learning background and language proficiency (see

Appendix). Both closed- and open-ended questions were used. Depending on whether they answered "yes" to the previous routing question, participants could skip Questions 7, 9, 11, 13, 15, 16, 19, and 22. The first seven questions were designed to collect background information such as age, gender, and factors that might affect their performance in the experiment. The remaining of questions were about language learning history and self-rated language proficiency, living abroad experience (including the length), self-reported foreign languages proficiency, and AOA. The questionnaire took approximately 5 to 10 minutes to complete.

Data Analysis

Data from all three tasks were analyzed with SPSS 22 for descriptive and inferential statistics. In the Reading Span task, participants, regardless of language group, were regrouped into high span (upper 25% percentile) and low span (lower 25% percentile). Using this grouping variable, Independent *T*-tests were conducted with Stop-Signal and Simon task data as dependent variables to determine the effect of working memory capacity on two varying aspects of inhibitory control. In addition, the three language groups were compared using one-way ANOVA to make sure there was no significant difference between them in terms of innate working memory capacity, due to the sampling method.

Data from the stop-signal paradigm were derived using the ANALYZE−IT program that came with the STOP-IT program (Verbruggen et al., 2008). Dependent measures tied to either stop-signal performance and no-signal performances, such as SSD, SSRT and no-signal RT, were each compared across the three language groups using one-way ANOVA. Shorter SSRT and longer SSD are indicators of greater inhibitory control. In addition, better inhibitory control should correlate with better performance in the no-signal trials (i.e., shorter RT), indicating flexibility in controlled and automatic processing.

For Simon task, RT and accuracy data were analyzed using a 3 (language groups) X 2 (span group) X 3 (sessions) repeated measures ANOVA. Trials with RTs <200ms or >1500ms were excluded from analyses. The results from the stop-signal paradigm and the Simon task were used to determine whether the three groups differed in the two aspects of cognitive processing.

Conceptual Models

In this study, structural equation modeling (SEM) was used to examine the effect of working memory capacity (represented by the variable of the reading span absolute score) on Simon task reaction time (RT) and accuracy, and on stop-signal RT (SSRT), stop-signal delay (SSD), no-signal RT (NS-RT), and no-signal correct responses (NS-HIT). Three conceptual models were proposed based on literature review and tested for goodness of fit, using AMOS 21. The first two conceptual models for the effect of working memory capacity (WM) on Simon task reaction time and accuracy were shown in Figure 3.1 and Figure 3.2 for congruent and incongruent trials, respectively. In both models, reading span absolute score (RSpan) was hypothesized to have direct influence on Simon task RT and response accuracy (ACC).

The third model (Figure 3.3), indicates the hypothesized effect of WM on SSRT, SSD, NS-RT, and NS-HIT. In this model, RSpan was assumed to have direct influence on the first three variables, but an indirect influence on NS-HIT.

This study chose SEM because of the following considerations. SEM can test various theoretical models that hypothesize how sets of variables define constructs and how these constructs are related to one another. It includes a set of linear structural equations. Variables in the equation system may be either directly observed variables or unmeasured latent (theoretical) variables that are not observed but relate to observed (manifest) variables. It is assumed in the model that there is a causal structure among a set of latent variables, and that the manifest variables are indicators of the latent variables (see Joreskog & Sorbom, 1989). Therefore, one of the two basic parts involved in SEM is the measurement model, which refers to the relationships between latent variables and their corresponding manifest variables. It specifies how latent variables or hypothetical constructs depend upon or are indicated by the manifest variables and describes the measurement properties (reliabilities and validities) of the manifest variables. In Figures 3.1 and 3.2, for example, ACC and RT are latent variables, each defined by three manifest variables (three sessions). Essentially, a latent variable is an underlying phenomenon that the manifest variables are intended to reflect. The measurement properties of a model can be investigated by inspecting the magnitude of the "loadings" of each manifest variable on its latent variable. These loadings reflect the correlation of the manifest variable with the latent variable. To the extent that the loadings are relatively high and statistically significant, there is evidence that the corresponding manifest variables contribute to the definition of the latent variable.

On the other hand, besides being a measurement model, SEM is characterized as a structural model that specifies the causal relationships among the latent variables, describes the causal effects, and assigns the explained and unexplained variance. All latent variables are further labeled exogenous or endogenous. The exogenous variables are those that are not affected by the other latent variables within the model, while the endogenous variables are those that are affected by other latent variables. In Figure 3.3, for example, RSpan is an exogenous variable while the other four variables are endogenous variables because they are assumed to be affected by the exogenous variable, RSpan.

One of SEM's strengths over the linear regression analysis is that an endogenous variable can serve as a dependent variable to one variable and as an independent variable to the other variable in the meantime (Joreskog & Sorbom, 1989). In Figure 3.3, NS-RT is assumed to be influenced by RSpan while it affects NS-HIT. In this sense, NS-RT is a dependent variable on RSpan, and at the same time it is an independent variable to NS-HIT. The relationship between NS-RT, RSpan, and NS-HIT cannot be revealed by linear regression. Furthermore, the structural model involves the calculation of path coefficients and determines whether the relationships proposed by the paths are significant. It assesses relationship or paths simultaneously, thus revealing unique relationships that are not confounded with other variables in the model.

In addition to indicating whether paths are significant, SEM can provide indices that indicate how well the conceptual model as a whole fits the data, or to determine the extent to which the model is consistent with the data. If goodness-of-fit is good enough, the model contends for the plausibility of hypothesized relations among variables; otherwise, the validity of such relations is rejected. To assess the overall model fit, indices commonly suggested in the SEM literature were used (e.g., Byrne, 2010), such as chi-square statistics (χ^2), p value, Chi Square / df ratio (χ^2/df), Goodness-of-Fit Index (GFI), Adjusted Goodness-of-Fit Index (AGFI), Comparative Fit Index (CFI), and Root

Mean Squared Error of Approximation (RMSEA). χ^2 is used to compare the sample covariance matrix and the covariance matrix implied. A nonsignificant χ^2 indicates that the model "fits" the data in that the model can reproduce the sample covariance matrix. However, χ^2 is sensitive to sample size, and relative χ^2 (i.e., Chi Square / df ratio) is often used to make it less dependent on sample size. Values of chi-square /df ratio less than or equal to two indicate adequate fit (Byrne, 2010).

GFI is based on a ratio of the sum of the squared discrepancies to the observed variances with values exceeding 0.9 indicating a good fit to the data. AGFI adjusts GFI for degrees of freedom, with values above 0.9, close to 1 indicating good fit. CFI ranges from 0 to 1 and is derived from the comparison of a hypothesized model with the independence/null model (which assumes no relationship among all variables), with values larger than 0.9 indicating good fit. RMSEA is based on the analysis of residuals, with smaller values indicating a better fit to the data, and values less than or equal to .06 are suggested as the cutoff for a good model fit (Hu & Bentler, 1999).

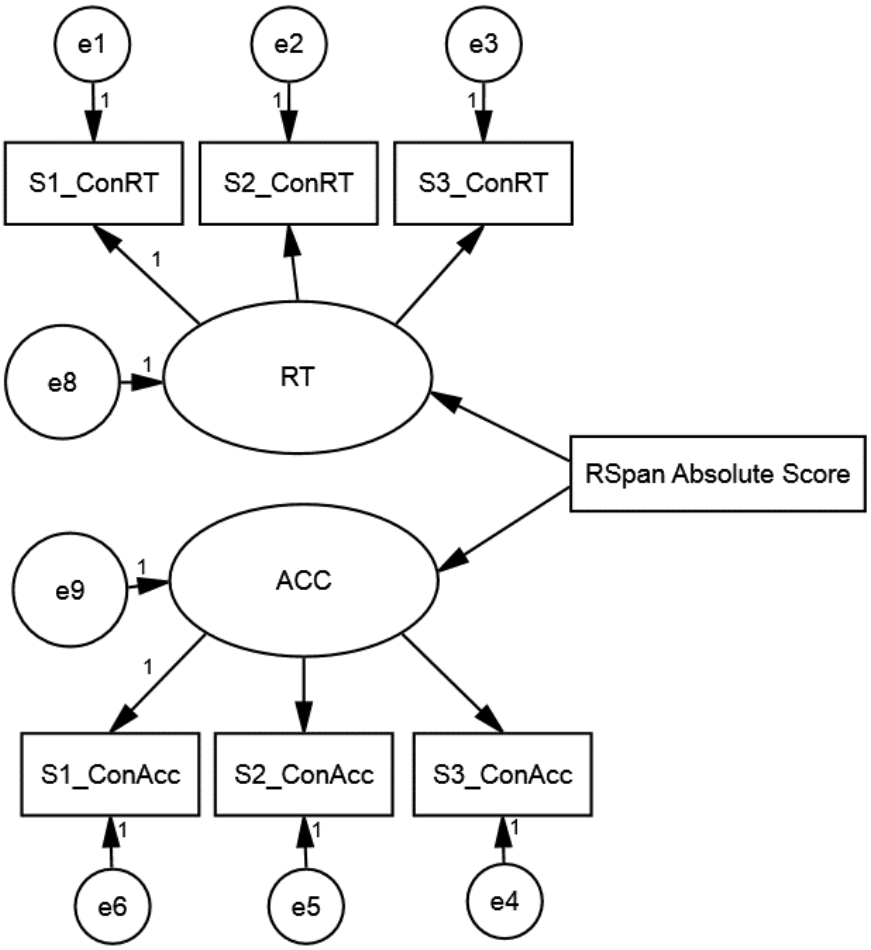

Figure 3.1. Conceptual Model of the Effect of WM on Congruent Trials RT and Accuracy
(RSpan Absolute Score = reading span absolute score; RT = Simon task reaction time; S1_ConRT = session 1 congruent trials reaction time; S2_ConRT = session 2 congruent trials reaction time; S3_ConRT = session 3 congruent trials reaction time; ACC = Simon task response accuracy; S1_ConAcc = session 1 congruent trials response accuracy; S2_ConAcc = session 2 congruent trials response accuracy; S3_ConAcc = session 3 congruent trials response accuracy)

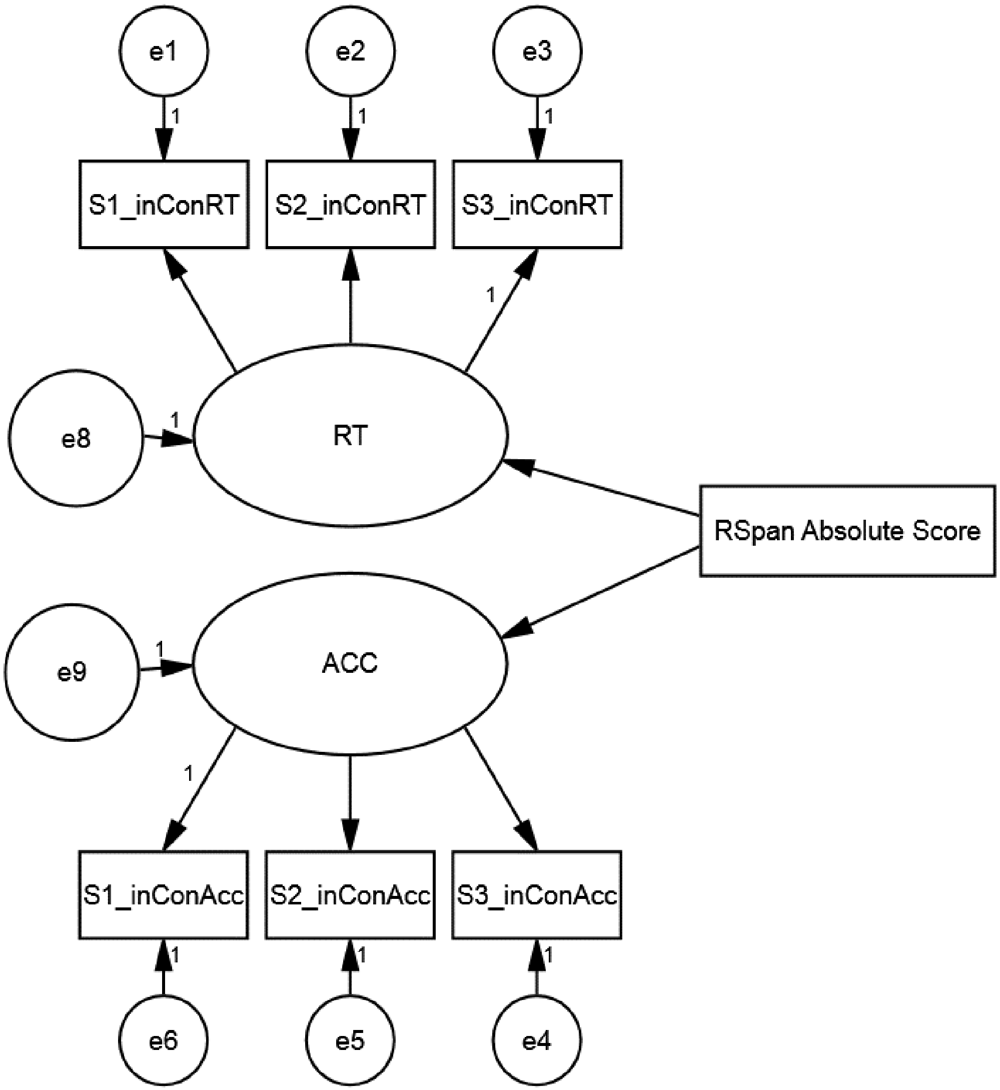

Figure 3.2. Conceptual Model of the Effect of WM on Incongruent Trials RT and Accuracy

(RSpan Absolute Score = reading span absolute score; RT = Simon task reaction time; S1_inConRT = session 1 incongruent trials reaction time; S2_inConRT = session 2 incongruent trials reaction time; S3_inConRT = session 3 incongruent trials reaction time; ACC = Simon task response accuracy; S1_inConAcc = session 1 incongruent trials response accuracy; S2_inConAcc = session 2 incongruent trials response accuracy; S3_inConAcc = session 3 incongruent trials response accuracy)

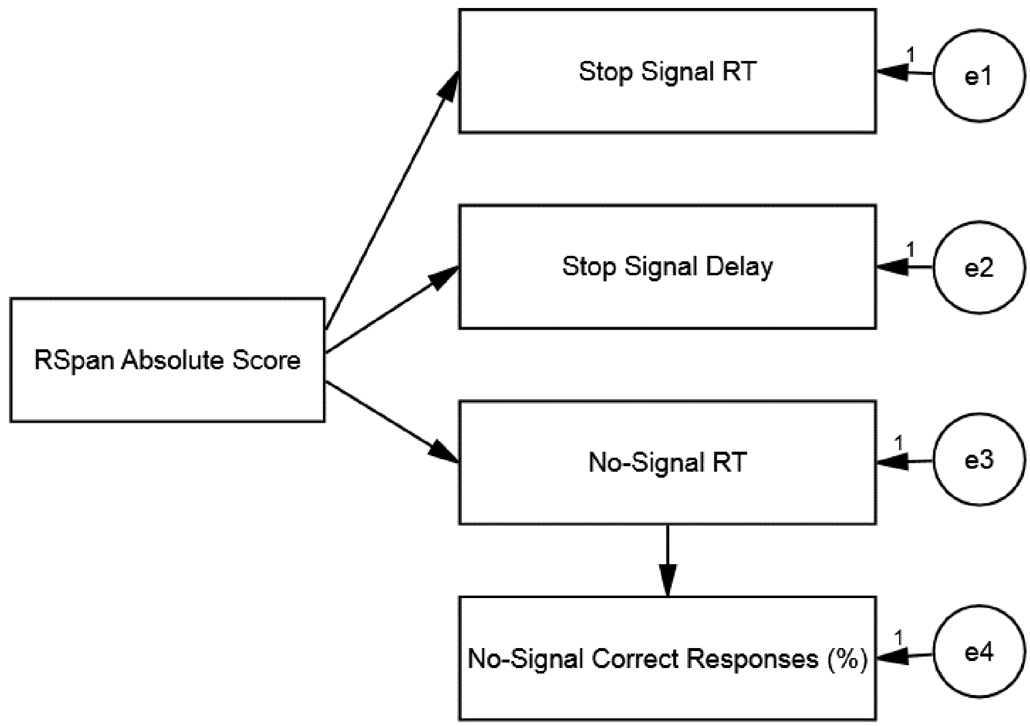

Figure 3.3. Conceptual Model of Working Memory Capacity’s Effect on Stop-Signal Task

CHAPTER 4

RESULTS

This chapter presents results from the three cognitive tasks: reading span, Simon task, and stop-signal paradigm. Results from group statistics and inferential statistics were reported. For Simon task and stop-signal paradigm, structural equation modeling was used to examine the casual relationship of the variables.

Reading Span Task

For this task, participants with reading accuracy that fell below 85% were excluded from analysis, resulting in removing five cases. Of the 176 remaining participants, the absolute score ranged from 7 to 75 (M = 37.86, SD = 15.76). The 25th percentile on the absolute score was 25, and the 75th was 49.75. Based on the quartiles, participants scored 25 or below formed the low span group (n = 46), and 49 or above formed the high span group (n = 49). One-way ANOVA was conducted on the reading span data to answer the first research question (RQ), whether the three language groups differ in working memory (WM) capacity.

Table 4.1 listed the descriptive statistics for the three groups. A test of homogeneity of variance (F (2, 173) = 2.46, p = .089) showed that equal variance could be assumed for these groups. As expected in Hypothesis 1, the results from one-way ANOVA indicated that there was no significant difference between these groups in terms of innate working memory capacity (F (2, 173) = .51, p = .600).

Stop−Signal Paradigm

For this task, participants with overall no-signal correct response accuracy (NS-HIT) <66%, or probability of inhibiting (p(r|s)) <13% or >85% were excluded from analyses because these values indicated a poor observation of task instructions and would produce unreliable estimates of stop-signal response time (SSRT) (Band, 1997). Data from 147 participants were analyzed for this task. Table 4.2 presents descriptive statistics for the three language groups on seven dependent variables.

Hypothesis 2 was not supported, as there were no significant group differences in any of the seven dependent variables, according to the one-way ANOVA results. Test of homogeneity of variance for all variables indicated that equal variance could be assumed for these groups. This answered RQ 2, whether the three language groups differed in stop-signal task performance.

This result was assumed for p(r|s), as its values were generated by the STOP-IT program. The program maintained each participant's probability of responding to stop-signals (unable to withhold key-pressing when there was a sound) to around 50%. The mean probabilities showed that on average, the EB group was the most likely to respond, while the LH group was the least likely (F (2, 144) = .41, p = .666).

Stop-signal delay (SSD) is the time lapse (milliseconds or ms) between presentations of the primary task stimulus (i.e., either a square or circle) and the auditory stop-signal (i.e., a tone). As mentioned in Chapter 3, this value was adjusted by the program based on participants' performance in previous stop-trials, and a longer SSD made the response inhibition after the onset of the stop-signal more challenging. The EB group had the shortest mean SSD, followed by the LH group (F (2, 144) = .35, p = .70).

Stop-signal response time (SSRT) is a variable that is estimated, rather than measured, by the STOP-IT program. It is the time (ms) between hearing the stop-signal and responding (internally) correctly by withholding the action of key pressing during the stop-trials. This is an estimation of the time it takes to inhibit the tendency to respond (pressing a key), given the stop-signal. By definition, this value appears to be derived from mean NS-RT minus the mean SSD. However, because "mean signal-respond RT and mean no-signal RT are calculated after the removal of incorrect responses (i.e., when the wrong key is pressed)" (Verbruggen, Logan, & Stevens, 2008, p. 482), this equation does not match actual data. The EB group had the longest mean SSRT, while the LH group had the shortest (F (2, 144) = .46, p = .634).

Signal-respond response time (SR-RT) is the time interval (ms) between the presentation of the visual stimulus and responding to the stop-signal during stop-trials. For reasons mentioned above, this does not match the sum of SSD and SSRT in actual data. Of the three groups, the EB group had the shortest mean RT, followed by the LH group (F (2, 144) = .71, p = .495).

No-signal response time (NS-RT) is the time (ms) it took to respond to the primary task, which was shape identification, during no-signal trials. This was a measurement of the baseline reaction time of the participants. The EB group again had shortest mean NS-RT, followed by the LH group (F (2, 144) = .27, p = .764).

No-signal correct responses (NS-HIT) measures the accuracy (percentage) of primary task responses during no-signal trials. The EB group showed the highest mean accuracy, followed by the LH group (F (2, 144) = .59, p = .558).

Missed Signals (MISS) is the percentage of missed trials, where no response was given to the primary task stimulus, during no-signal trials. Similar to NS-HIT, the EB group missed the least trials, followed by the LH group (F (2, 144) = .50, p = .609).

RQ 3 was answered by comparing high span and low span groups. Table 4.3 reported the descriptive statistics. Independent samples *T*-test found a significant difference between the high span and low span groups in SSRT (t (81) = -2.60, p = .011). This difference indicated that the high span group was significantly faster in inhibiting the primary task response (shape identification) when there was a stop signal. No significant group differences were found for the rest of the six dependent variables.

Linear regression analysis on four RT and accuracy measures was conducted to provide answers to RQ 4, the relationships between RT and accuracy. Results for the three language groups are shown in Tables 4.4 to 4.6.

Regression analysis was used to test if no-signal RT significantly predicted no-signal correct responses (see Table 4. 4). The results indicated a significant negative causal relationship, which was contrary to the prediction of Hypothesis 4 (expected a positive correlation). For the EB group, NS-RT explained 23% of the variance (R^2 = .23, F (1, 46) = 13.71, p = .001) in NS-HIT. The regression coefficient means that when NS-RT increased by 1 ms, the response accuracy decreased by 0.48% (β = .48, p = .001). For the LH group, NS-RT explained 14% of the variance (R^2 = .14, F (1, 63) = 10.15, p = .002) in NS-HIT. The regression coefficient means that when NS-RT increased by 1 ms, the response accuracy decreased by 0.37% (β = .37, p = .002). For the LL group, NS-

RT explained 20% of the variance (R^2 = .20, F (1, 32) = 7.75, p = .009) in NS-HIT. The regression coefficient means that when NS-RT increased by 1 ms, the response accuracy decrease by 0.44% (β = .44, p = .009). Overall, the results suggested that the primary task (i.e., shape identification) did not cause much cognitive load to participants; when they responded faster, the accuracy was higher.

The casual relationship between stop-signal RT and no-signal RT was examined to see if the former could be predicted by the latter: in other words, whether the faster RT in primary task trials would result in fast RT in stop-signal trials. As shown in Table 4.5, no statistically significant linear dependence of the mean of SSRT on NSRT was detected in any of the three groups.

Regression analysis was also conducted on the two dependent variables SSD and SSRT, indicators of stop-signal performance (see Table 4.6). For the EB group, no statistically significant linear dependence of the mean of SSRT on SSD was detected (F (1, 46) = .13, p = .720). For the LH group, SSD explained 17% of the variance (R^2 = .17, F (1, 63) = 12.97, p = .001) in SSRT. The regression coefficient means that when SSD increased by 1 ms, the SSRT decrease by .41 ms (β = .41, p = .001). For the LL group, SSD explained 13% of the variance (R^2 = .13, F (1, 32) = 4.62, p = .039) in SSRT, and that when SSD increased by 1 ms, the SSRT decreased by .36 ms (β = .36, p = .039).

Simon Task

This task consists of three sessions, with 400 trials each. Trials with RTs <200ms or >1500ms were excluded from all analyses, removing approximately 1% of the data. RT and accuracy data for congruent and incongruent trials were analyzed separately using a 3 (language groups) X 2 (span group) X 3 (session) repeated measures ANOVA. As Mauchly's Test of Sphericity was significant, which means equality of variance could not be assumed, data were corrected using Greenhouse-Geisser. No significant differences were found in any of the dependent variables. Table 4.7 to 4.9 reported the descriptive statistics for the three language groups.

Therefore, for RQ 5, no significant differences were found among the three groups. However, the overall trend was that there was a decrease in reaction time across the three sessions. In other words, all three groups seemed to be responding faster with practice. The EB group had the fastest reaction time in both congruent and incongruent trials, followed by the LH group. The EB group also had the highest accuracy rate for incongruent trials, and the LL group had the lowest. For congruent trials, the EB group had the lowest accuracy rate, while the other two groups had similar rates. In addition, the EB group showed the smallest Simon effect (Incongruent RT – Congruent RT), and the LL group had the largest Simon effect. This means that the early bilinguals were the least likely to be interfered with by the arrow direction location mismatch in the Simon task.

For the high/low span groups, the results were similar, with the high span group outperforming the low span group in every measurement; however, no significant differences were found. The descriptive statistics are listed in Table 4.10.

Regression analysis was conducted to answer RQ 6, the relationships between RT and accuracy. Table 4.11 reported the statistics from congruent trials. For the EB group, no statistically significant linear dependence of the mean of congruent trials accuracy on RT was detected (F (1, 53) = 1.30, p = .260). For the LH group, no statistically significant linear dependence of the mean of congruent trials accuracy on RT was detected (F (1, 77) = .58, p = .448). For the LL group, RT explained 14% of the variance (R^2 = .14, F (1, 43) = 6.58, p = .014) in accuracy rate. The rate of change of the conditional mean accuracy with respect to RT is about .37. This regression coefficient means that when RT increased by 1 ms, the accuracy rate increased by .37% (β = .37, p = .014). This is an indication that the LL group was affected by speed-accuracy tradeoff during congruent trials, as faster RT would lead to a lower response accuracy.

The results from incongruent trials were shown in Table 4.12. For the EB group, no statistically significant linear dependence of the mean of incongruent trials accuracy on RT was detected (F (1, 53) = 2.01, p = .162). For the LH group, RT explained 9% of the variance (R^2 = .09, F (1, 77) = 7.61, p = .007) in accuracy rate. The rate of change of the conditional mean accuracy with respect to RT is about .30. This regression coefficient means that when RT increased by 1 ms, the accuracy rate increased by .30% (β = .30, p = .007). For the LL group, RT explained 16% of the variance (R^2 = .16, F (1, 43) = 8.25, p = .006) in accuracy rate. The regression coefficient means that when RT increased by 1 ms, the accuracy rate increased by .41% (β = .41, p = .006). This is an indication that both the LH and LL groups were affected by the speed-accuracy tradeoff during incongruent trials.

Structural Equation Modeling

The Effect of Working Memory Capacity on Simon Task RT and Accuracy

For RQ7, the relationship between WM and interference control, which was measured by the Simon task, was examined using structural equation modeling (SEM) with the maximum likelihood extraction method. The purpose was to conduct model estimates for the two conceptual models concerning WM's effects on congruent/ incongruent trials proposed in Chapter 3 (Figures 3.1 and 3.2).

Table 4.13 presents the indices assessing the overall model fit for the initial model and revised model for congruent trials. Due to the required SEM model fit indices (p >.05; $\chi^2/df \leqslant 2$; GFI, AGFI, CFI$\geqslant$.90; RMSEA$\leqslant$.06) (Byrne, 2010), the conceptual model was rejected (p = .007, χ^2/df = 2.21, and RMSEA = .083). This result indicated that the model did not fit the data well, and the model needed modifications. As suggested by the modification indices of AMOS, two double-arrow paths (indicating covariance) were added to the initial model to link two pairs of residuals/errors indicating that there was covariance in each pair (between Error 1 and Error 6, Error 4 and Error 8). Subsequently, all the model fit indices met the SEM requirements. In the revised or final model, the null hypothesis that the implied (sample) covariance matrix equals population covariance matrix was accepted (p = .099). In other words, the revised model based on the sample could reproduce the population covariance matrix (χ^2/df = 1.574, GFI = .974, AGFI = .934, CFI = .992, and RMSEA = .057). All these indices suggested a good fit between the model and the data.

The paths and their standardized coefficients were shown in Figure 4.1. For two latent variables (RT and accuracy), all path coefficients pointing to manifest variables, ranging from .32 to 1.12, were significant, which implied that all the manifest variables defined the latent variables validly. The path coefficients from RSpan Absolute Score (measurement of WM, subsequently referred to as RSpan) to RT and ACC were -.12 and -.03, respectively. To be more specific, the two path coefficients suggested that if RSpan increased by one standard deviation from its mean, RT could be expected to decrease by

0.12 of its own standard deviation from its mean while holding all other variables constant. In addition, response accuracy could decrease by 0.03 of its standard deviation from its mean while holding all other variables constant. However, it should be pointed out that these two path coefficients were not significant (p = .407 and .174, respectively). Therefore, no statistically significant effect of WM on RT and ACC was found in the congruent trials.

Table 4.14 listed the model fit indices for incongruent trials, to test the conceptual model concerning WM's effect on RT and accuracy for incongruent trials (see Figure 3.2). As indicated in Table 4.14, the initial model was not accepted (p =.000, $\chi 2/df$ = 3.436, AGFI = .861, and RMSEA = .118). Based on modification indices, two double-arrow paths were added to the initial model between error 3 and error 4, and error 8 and error 9, indicating covariances. This revised model (Figure 4.2) fits the data well (p =.161, $\chi 2/df$ = 1.408, AGFI = .939, and RMSEA = .048).

As indicated in Figure 4.2, the latent variables of RT and ACC in incongruent trials were well defined with loadings ranging from .81 to .98. The path coefficient of -.14 from RSpan to RT implies that if RSpan increased by one standard deviation from its mean, RT could be expected to decrease by 0.14 of its standard deviation from its mean while holding all other variables constant. The path coefficient of .03 from RSpan to ACC implies that if RSpan increased by one standard deviation from its mean, response accuracy could be expected to increase by .03 of its standard deviation from its mean while holding all other variables constant. However, these two path coefficients were not significant (p = .059 and .730, respectively). Therefore, no statistically significant effect of WM on RT and ACC was found in the incongruent trials, either.

Working Memory's Effect on Stop-Signal Task

In the conceptual model (see Figure 3.3), RSpan was hypothesized to have direct influence on stop-signal RT (SSRT), stop-signal delay (SSD), no-signal RT (NS-RT), and indirect influence on no-signal correct responses rate (NS-HIT). The proposed model only included manifest variables without latent variables, except for the residuals/errors. The overall model fit indices were reported in Table 4.15. The conceptual model did not fit the data (p = .000, χ^2/df ratio = 219.788, GFI = .709, AGFI = .272, CFI = .023, RMSEA = 1.224).

Following the modification indices in AMOS output, two double-arrow paths (indicating covariance) between Errors 1 and 2, 2 and 3 were added to improve the model. The revised model (Figure 4.3) met all the model fit indices and could be accepted (p = .570, χ^2/df ratio = .732, GFI = .992, AGFI = .970, CFI = 1.000, RMSEA = .000). All these indices show that the revised model fits the data well.

As indicated in the final model (Figure 4.3), RSpan had positive effect on stop-signal delay while negative effect on stop-signal RT and no-signal RT. It had a negative indirect effect on no-signal correct responses (%), mediated by no-signal RT. However, the standardized path coefficients from RSpan to stop-signal delay and no-signal RT were quite low (.01 and -.05, respectively), and not statistically significant (p = .857 and .537, respectively). The standardized path coefficient (-.23) from RSpan to stop-signal RT was statistically significant (p = .005), and the standardized path coefficient (-.41) from no-signal RT to no-signal correct responses (%) was also significant (p < .001). The path coefficient of -.23 from RSpan to stop-signal RT indicated that when RSpan increased by one standard deviation from its mean, stop-signal RT would decrease by 0.23 its standard deviation from its mean, while holding all other variables constant. The standardized path coefficient (-.41) from no-signal RT to no-signal correct responses rate (%) indicates that an increase of NS-RT by one standard deviation from its mean would lead to a decrease of NS-HIT by 0.41 its standard deviation from its mean, while holding all other variables constant.

To sum up, SEM through AMOS was used in this study to test the three conceptual models concerning the role of WM capacity in the Simon task and the stop-signal paradigm. All three models fit the data well after minor modifications. For both congruent and incongruent trials in the Simon task, a statistically significant influence of WM on RT and response accuracy was not detected. For the stop-signal paradigm, mixed results were obtained. WM had a significant negative direct effect on stop-signal RT, and a significant negative indirect effect on no-signal correct responses rate through no-signal RT.

Table 4.1

Group Statistics for Reading Span Absolute Score

				95% Confidence Interval for Mean	
Group	*n*	*M*	*SD*	Lower Bound	Upper Bound
EB	54	37.89	17.87	33.01	42.77
LH	78	36.76	15.43	33.28	40.23
LL	44	39.78	13.63	35.63	43.92
Total	176	37.86	15.76	35.51	40.20

Note. EB = early bilingual group, LH = late bilingual high proficiency group, LL = late bilingual low proficiency group

Table 4.2

Language Group Statistics for Stop-Signal Task

Measure	Group	*n*	*M*	*SD*	95% Confidence Interval for Mean	
					Lower Bound	Upper Bound
p(r|s)	EB	48	47.57	4.83	46.16	48.97
	LH	65	46.82	4.32	45.75	47.89
	LL	34	47.43	4.92	45.71	49.14
	Total	147	47.21	4.61	46.45	47.96
Stop-Signal Delay (SSD)	EB	48	353.26	131.53	315.07	391.45
	LH	65	376.86	164.59	336.08	417.65
	LL	34	376.39	182.21	312.81	439.96
	Total	147	369.04	158.33	343.24	394.85
Stop-Signal RT (SSRT)	EB	48	247.91	41.65	235.81	260.00
	LH	65	240.66	43.98	229.76	251.56
	LL	34	247.46	49.27	230.27	264.65
	Total	147	244.60	44.36	237.37	251.83
Signal-Respond RT (SR-RT)	EB	48	523.32	113.78	490.28	556.36
	LH	65	549.51	134.17	516.26	582.75
	LL	34	552.77	147.41	501.34	604.21
	Total	147	541.71	130.91	520.37	563.05
No-Signal RT (NS-RT)	EB	48	601.49	135.83	562.05	640.93
	LH	65	618.10	151.37	580.59	655.61
	LL	34	624.47	170.49	564.98	683.95
	Total	147	614.15	150.46	589.62	638.68
No-signal Correct Responses (%) (NS-HIT)	EB	48	97.90	2.65	97.13	98.67
	LH	65	97.50	4.24	96.45	98.55
	LL	34	96.95	4.69	95.31	98.59
	Total	147	97.50	3.91	96.87	98.14
No-signal Missed Responses (%) (MISS)	EB	48	1.23	2.31	.56	1.91
	LH	65	1.84	4.27	.78	2.90
	LL	34	1.95	4.16	.50	3.40
	Total	147	1.67	3.70	1.06	2.27

Table 4.3

Span Group Statistics for Stop-Signal Task

Measure	Group	*n*	*M*	*SD*
p(r|s)	High Span	41	48.26	5.17
	Low Span	42	47.74	4.56
Stop-Signal Delay	High Span	41	382.87	178.66
	Low Span	42	341.70	132.94
Stop-Signal RT	High Span	41	234.13	42.48
	Low Span	42	261.62	53.08
Signal-Respond RT	High Span	41	541.04	147.36
	Low Span	42	532.06	98.59
No-Signal RT	High Span	41	617.40	167.90
	Low Span	42	603.70	127.26
No-signal Correct Responses (%)	High Span	41	97.53	3.57
	Low Span	42	97.08	4.52
No-signal Missed Responses (%)	High Span	41	1.49	2.85
	Low Span	42	2.03	4.42

Table 4.4

Regression Analysis on NS-RT and NS-HIT

	Coefficient [a, b]				
Group	*βeta*	*t*	*Sig.*	R^2	*F (Sig.)*
EB	-.48	-3.70	.001	.23	13.71 (.001)
LH	-.37	-3.19	.002	.14	10.15 (.002)
LL	-.44	-2.78	.009	.20	7.75 (.009)

a. Dependent Variable: No-signal Correct Responses (%)
b. Independent Variable: No-Signal RT (ms)

Table 4.5

Regression Analysis on NS-RT and SSRT

	Coefficient [a, b]				
Group	*βeta*	*t*	*Sig.*	R^2	*F (Sig.)*
EB	.26	1.79	.080	.07	3.21 (.080)
LH	-.16	-1.30	.197	.03	1.70 (.197)
LL	-.09	-.49	.625	.01	.24 (.625)

a. Dependent Variable: Stop-Signal RT
b. Independent Variable: No-Signal RT

Table 4.6

Regression Analysis on SSD and SSRT

	Coefficient [a, b]				
Group	*βeta*	*t*	*Sig.*	R^2	*F (Sig.)*
EB	-.05	-.36	.720	.003	.13 (.720)
LH	-.41	-3.60	.001	.17	12.97 (.001)
LL	-.36	-2.15	.039	.13	4.62 (.039)

a. Dependent Variable: Stop-Signal RT
b. Independent Variable: Stop-Signal Delay

Table 4.7

Descriptive Statistics for Early Bilingual Group (n = 54)

	M	*SD*
Session 1 Congruent RT	404.53	63.62
Session 2 Congruent RT	373.51	48.83
Session 3 Congruent RT	364.11	44.50
Session 1 Incongruent RT	497.58	91.65
Session 2 Incongruent RT	453.33	68.24
Session 3 Incongruent RT	446.21	59.54
Session 1 Congruent Accuracy	.99	.01
Session 2 Congruent Accuracy	.98	.06
Session 3 Congruent Accuracy	.98	.03
Session 1 Incongruent Accuracy	.89	.08
Session 2 Incongruent Accuracy	.87	.09
Session 3 Incongruent Accuracy	.84	.11
Mean Simon Effect	84.99	34.36

Table 4.8

Descriptive Statistics for Late Bilinguals High Proficiency Group (n = 78)

	M	*SD*
Session 1 Congruent RT	407.49	51.54
Session 2 Congruent RT	376.41	37.18
Session 3 Congruent RT	368.83	37.46
Session 1 Incongruent RT	506.99	74.42
Session 2 Incongruent RT	469.20	55.08
Session 3 Incongruent RT	455.77	53.75
Session 1 Congruent Accuracy	.99	.02
Session 2 Congruent Accuracy	.99	.01
Session 3 Congruent Accuracy	.99	.01
Session 1 Incongruent Accuracy	.86	.09
Session 2 Incongruent Accuracy	.85	.10
Session 3 Incongruent Accuracy	.83	.11
Mean Simon Effect	93.08	30.38

Table 4.9

Descriptive Statistics for Late Bilinguals Low Proficiency Group (n = 44)

	M	*SD*
Session 1 Congruent RT	417.06	71.96
Session 2 Congruent RT	382.34	62.59
Session 3 Congruent RT	369.88	53.78
Session 1 Incongruent RT	516.90	96.97
Session 2 Incongruent RT	473.33	84.61
Session 3 Incongruent RT	461.04	71.45
Session 1 Congruent Accuracy	.99	.01
Session 2 Congruent Accuracy	.99	.01
Session 3 Congruent Accuracy	.99	.01
Session 1 Incongruent Accuracy	.85	.10
Session 2 Incongruent Accuracy	.83	.11
Session 3 Incongruent Accuracy	.80	.14
Mean Simon Effect	94.00	33.53

Table 4.10

Descriptive Statistics for High and Low Span Groups

	Group	*n*	*M*	*SD*
Mean Congruent RT	High Span	49	379.33	53.61
	Low Span	46	394.01	55.79
Mean Incongruent RT	High Span	49	469.63	79.85
	Low Span	46	490.20	74.61
Mean Congruent Accuracy	High Span	49	.99	.01
	Low Span	46	.98	.03
Mean Incongruent Accuracy	High Span	49	.86	.11
	Low Span	46	.83	.11
Mean Simon Effect	High Span	49	90.30	36.15
	Low Span	46	96.19	33.58

Table 4.11

Regression Analysis on RT and Accuracy From Congruent Trials

	Coefficient [a, b]				
Group	*βeta*	*t*	*Sig.*	R^2	*F (Sig.)*
EB	-.16	-1.14	.260	.02	1.30 (.260)
LH	.09	.76	.448	.01	.58 (.448)
LL	.37	2.57	.014	.14	6.58 (.014)

a. Dependent Variable: Mean Congruent Accuracy
b. Independent Variable: Mean Congruent RT

Table 4.12

Regression Analysis on RT and Accuracy From Incongruent Trials

	Coefficient [a, b]				
Group	*βeta*	*t*	*Sig.*	R^2	*F (Sig.)*
EB	.19	1.42	.162	.04	2.01 (.162)
LH	.30	2.76	.007	.09	7.61 (.007)
LL	.41	2.87	.006	.16	8.25 (.006)

a. Dependent Variable: Mean Incongruent Accuracy
b. Independent Variable: Mean Incongruent RT

Table 4.13

Overall Model Fit Indices of Initial and Revised Models for Congruent Trials

Models	χ^2	df	p	χ^2/df	GFI	AGFI	CFI	RMSEA
Initial	28.728	13	*.007*	*2.210*	.957	.908	.981	*.083*
Revised	17.31	11	.099	1.574	.974	.934	.992	.057

Table 4.14

Overall Model Fit Indices of Initial and Revised Models for Incongruent Trials

Models	χ^2	df	p	χ^2/df	GFI	AGFI	CFI	RMSEA
Initial	44.665	13	*.000*	*3.436*	.935	*.861*	.967	*.118*
Revised	15.489	11	.161	1.408	.976	.939	.995	.048

Table 4.15

Overall Model Fit Indices of Initial and Revised Models for Stop-Signal Task

Models	χ^2	df	p	χ^2/df	GFI	AGFI	CFI	RMSEA
Initial	1318.728	6	*.000*	*219.788*	*.709*	*.272*	*.023*	*1.224*
Revised	2.930	4	.570	.732	.992	.970	1.000	.000

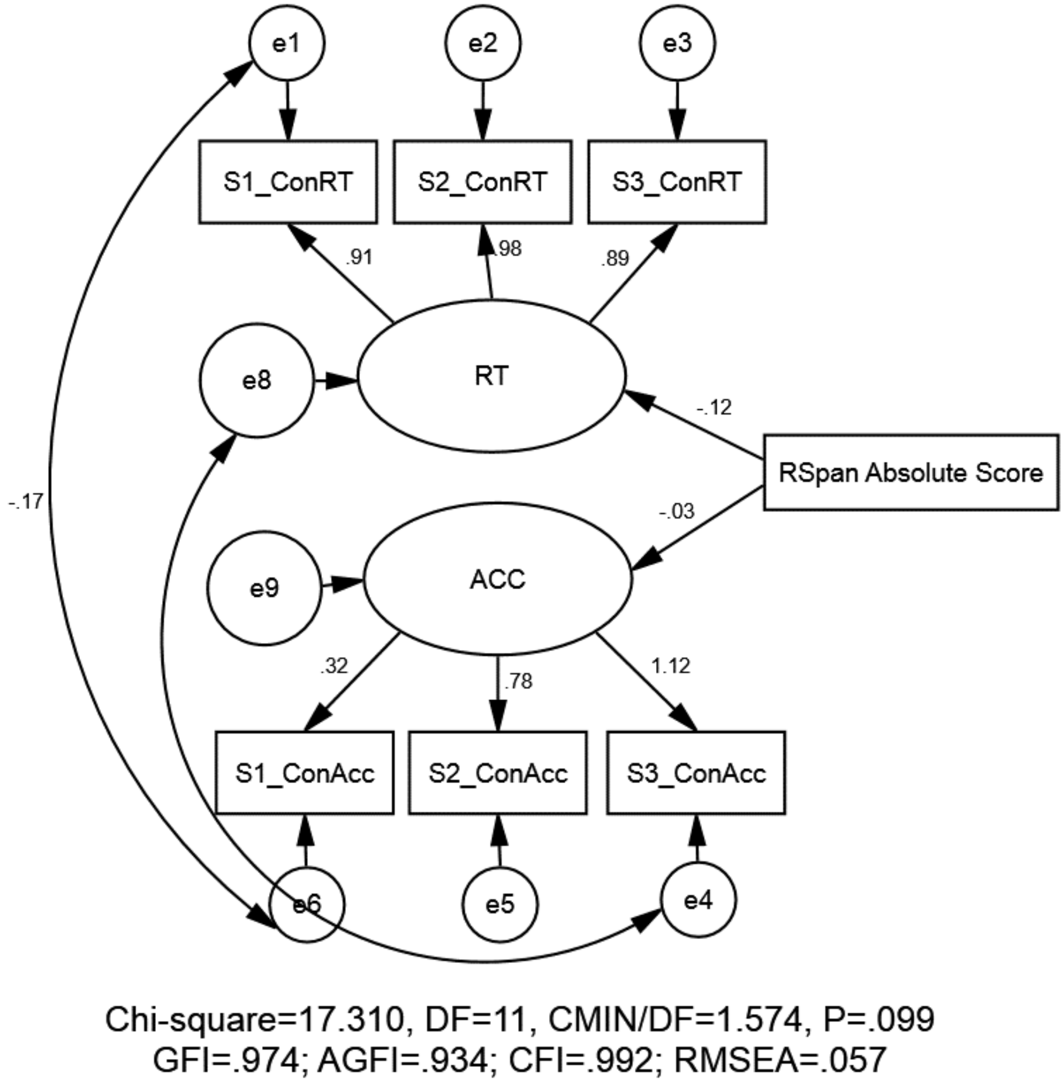

Figure 4.1. Final Model of the Effect of WM on Congruent Trials RT and Accuracy
(RSpan Absolute Score = reading span absolute score; RT = Simon task reaction time; S1_ConRT = session 1 congruent trials reaction time; S2_ConRT = session 2 congruent trials reaction time; S3_ConRT = session 3 congruent trials reaction time; ACC = Simon task response accuracy; S1_ConAcc = session 1 congruent trials response accuracy; S2_ConAcc = session 2 congruent trials response accuracy; S3_ConAcc = session 3 congruent trials response accuracy)

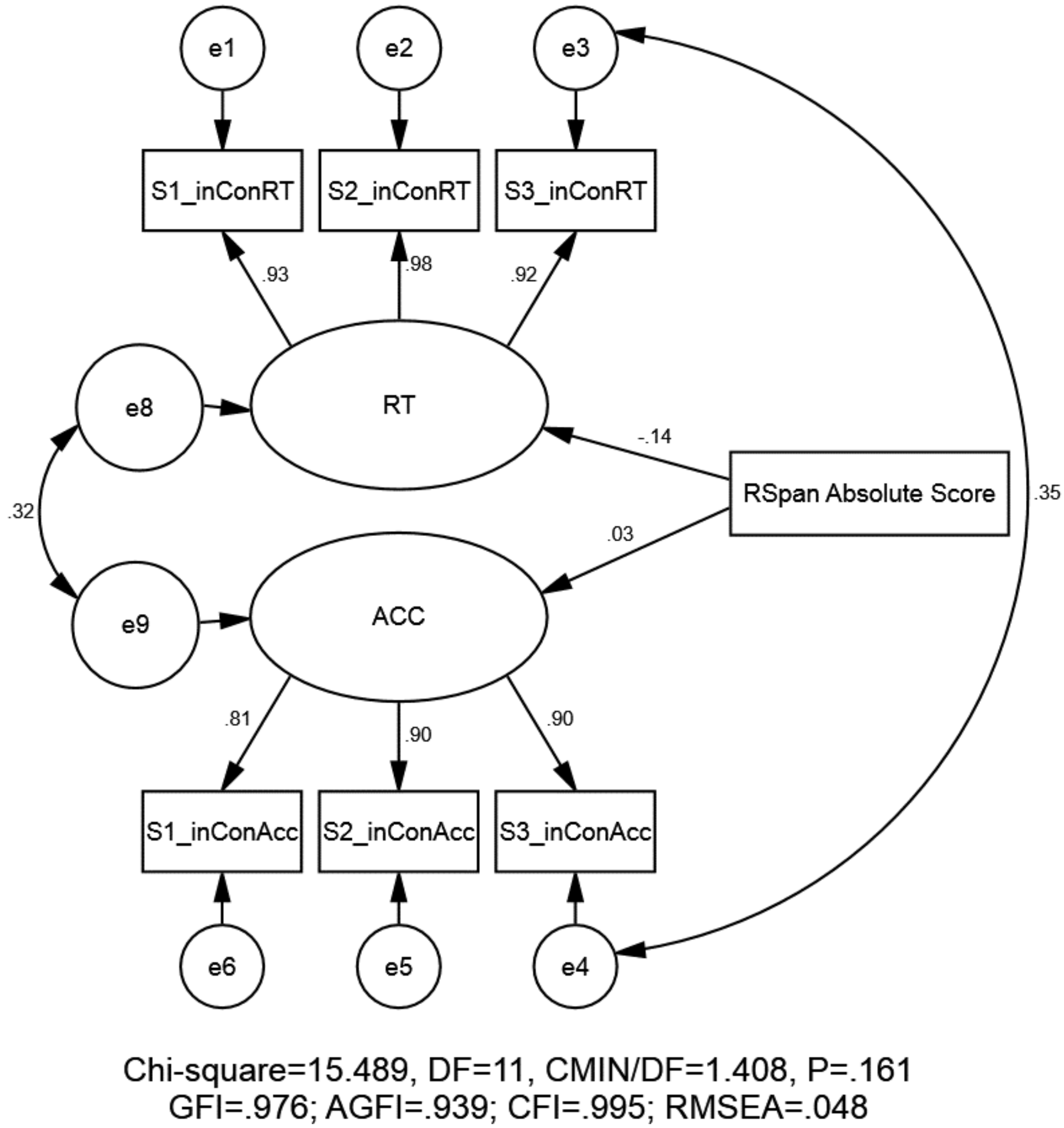

Figure 4.2. Final Model of the Effect of WM on Incongruent Trials RT and Accuracy
(RSpan Absolute Score = reading span absolute score; RT = Simon task reaction time; S1_inConRT = session 1 incongruent trials reaction time; S2_inConRT = session 2 incongruent trials reaction time; S3_inConRT = session 3 incongruent trials reaction time; ACC = Simon task response accuracy; S1_inConAcc = session 1 incongruent trials response accuracy; S2_inConAcc = session 2 incongruent trials response accuracy; S3_inConAcc = session 3 incongruent trials response accuracy)

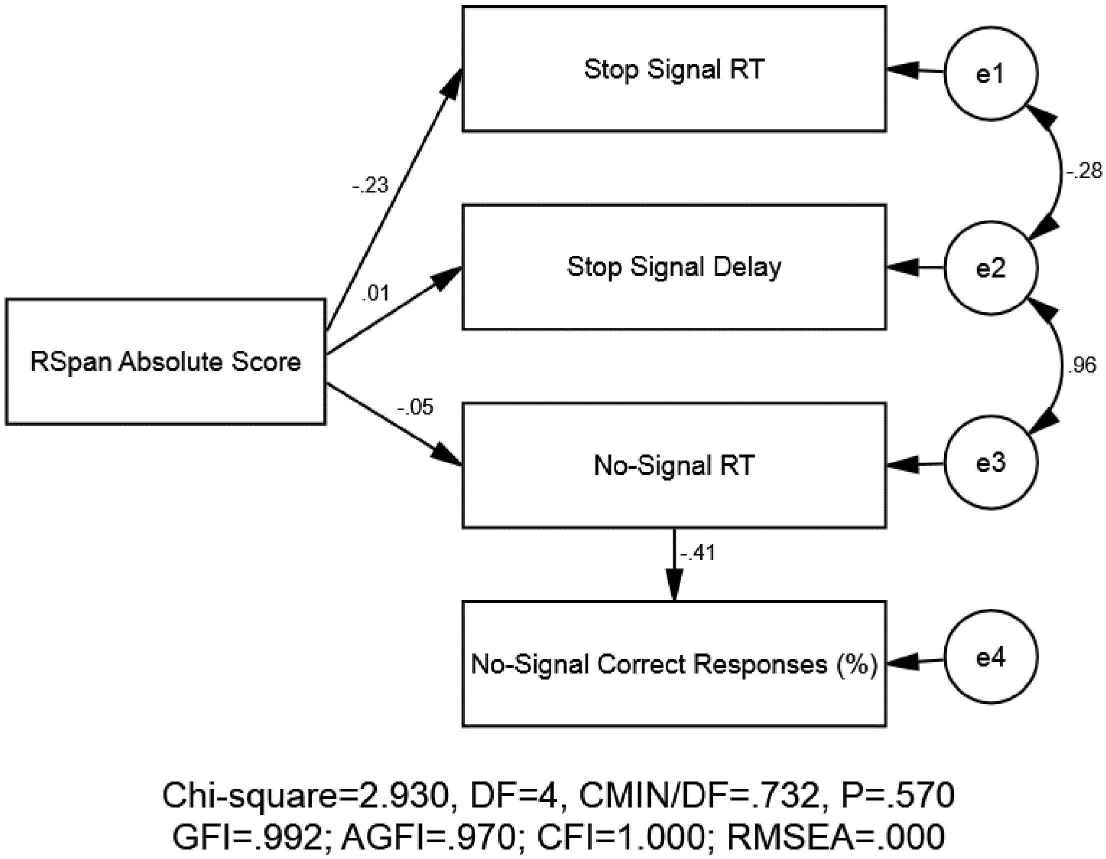

Figure 4.3. Final Model of Working Memory Capacity’s Effect on Stop-Signal Task

CHAPTER 5

DISCUSSION

This chapter discusses results from the three cognitive tasks—the reading span, Simon task, and stop-signal paradigm. Results from this study are discussed in terms of how factors, such as bilingualism and working memory, affect cognitive tasks involving interference control. Results from previous studies are also discussed here and compared with the current study.

The Role of Working Memory Capacity

For the first research question (RQ), whether or not the three bilingual groups differ in working memory capacity (WMC), this study found no significant difference among the three groups, even though the early bilingual (EB) group had the lowest mean reading span absolute score (RSpan) and the late low proficiency bilingual group (LL) had the highest. The finding that the age of acquisition (AOA) and foreign or second language (L2) proficiency had no significant relation with WMC was expected for Hypothesis 1, as all participants were college students and the possible variable of educational level was controlled. In addition, WMC is largely a genetically determined trait (Heck et al., 2014) that is stable within an individual, and does not respond to training (Melby-Lervåg, Redick, & Hulme, 2016). Similar findings came from studies by

Ratiu and Azuma (2015), who reported no evidence of a bilingual advantage in WMC between bilinguals and monolinguals who were college undergraduates. A recent study (Yang & Yang, 2017) using the operation span task (a WMC measurement that highly correlates with reading span) found no significant bilingual advantage in young adults. However, this is not the case for research on WMC developments in bilingual children. For instance, Morales, Calvo, and Bialystok (2013) compared 5- and 7-year-olds using two versions of the frogs matrices task, an age appropriate adaptation of the Corsi block-tapping test that measured visual-spatial WM. They concluded that the bilingual WM advantage was only obvious when cognitive control requirements were demanding. Similar findings came from a longitudinal study (Blom, Küntay, Messer, Verhagen, & Leseman, 2014) that compared Dutch monolinguals and Turkish–Dutch bilinguals at ages 5 and 6, using four sets of WM tasks. The results from this study show that bilinguals perform significantly better in one visuospatial task (i.e., Dot Matrix) and one verbal working memory task (i.e., Backward Digit Recall) at age 6 but not at age 5. As the bilinguals in their study had an AOA between ages 2 and 4, their findings provided partial evidence that WM capacity could be improved as a result of early L2 exposure. The tasks they used, however, may not adequately reflect the nature of WMC (cf., Conway et al., 2005). Because the study did not include a monolingual control group, it is unclear whether or not acquiring a new language improves WMC, and if improvement is possible, whether or not it is related to AOA, L2 proficiency, or the frequency of L2 use. The last two studies pointed to the possibility that WMC gains could be observed in early bilinguals at a young age. Therefore, it seems that longitudinal studies comparing monolingual, early bilinguals, and late bilinguals are needed to clarify the effects of bilingualism on WMC.

Structure equation modeling (SEM) was used in the current study to explore how WMC affects interference control and response inhibition, because WMC has been considered as a good predictor of performances on challenging cognitive tasks (e.g., Engle, 2002; Redick et al., 2016), with high WMC individuals exhibiting high task engagement. While no significant influence of WMC on interference control was found using the Simon task, WMC had a significant negative effect on stop-signal RT and a significant indirect effect on no-signal correct responses (%), mediated by no-signal RT. This result should not be interpreted as a dissociation between the two cognitive constructs because some studies using SEM found a moderate correlation between WMC and the two constructs respectively (e.g., Wilhelm, Hildebrandt, & Oberauer, 2013). In the present study, a high standard error caused by high variability among participants (i.e., a high standard derivation in WMC and other measurements) led to the difficulty of observing significant relationships and increasing study power (e.g., through enlarging sample size, adopting matched pairs design, or controlling for individual differences in social-economic status by using judgement sampling) may solve this problem. It is also likely that these two cognitive constructs tapped into different components of WMC, for example, monitoring, selecting, updating, and so forth. Therefore, extra working memory load (e.g., distraction) should be added to the Simon task in order to differentiate young adults with varying WMC because previous studies reported that when no significant relationship between WMC and task performance was found, adding a distraction made a difference (Kane, Poole, Tuholski, & Engle, 2006; Poole & Kane, 2009).

Bilingualism and Response Inhibition

In this study, stop-signal paradigm (SSP) was used to look into whether or not learning a second language involves the development of response inhibition, which is an aspect of cognitive control. Of the three language groups, the EB group had the fastest signal respond RT (i.e., SR-RT) and no-signal RT (NS-RT), and the LL group had the longest RT in both measures. When it came to response accuracy in no-signal trials, the EB group had the highest accuracy, followed by the late high proficiency bilingual group (LH). The LL group had the highest percentage of missed no-signal trials, while the EB group had the lowest. This result suggests a trend; in other words, the EB group seemed to respond faster, with better accuracy, in no-signal trials only. The trend seems to suggest the EB group was the most efficient at automatic processing and performed best in trials with no response inhibition involved, which is indicated by their fast RT and high accuracy rate), followed by the LH group. However, for RQ 2, whether the three language groups differed in their task performance, no significant group differences were found in terms of mean RT and accuracy, even after controlling for their reading span scores. With respect to the cognitive processes tapped into by suppressing prepotent responses, the trend is that the two late bilingual groups outperformed the EB group.

For the two dependent measures that reflected the stop-signal trials performance (efficiency of inhibitory control), the EB group had the shortest stop-signal delay (SSD) and the longest stop-signal RT (SSRT), while the LH group had the longest SSD and the shortest SSRT. Longer SSD is an indicator of higher tolerance for automatic response activation, while shorter SSRT is an indicator of better inhibitory processing that leads to faster RT in shutting down the automatically activated response (Kramer, Humphrey, Larish, & Logan, 1994; Logan et al., 1997). In other words, participants with long SSD and short SSRT were able to quickly withhold their habitual response (e.g., pressing a key when a shape was presented) to a stimulus (e.g., a shape) when a random stop signal (e.g., a sound) was presented after the usual stimulus, even when the stop signal was given relatively late after the stimulus. Therefore, the mean SSD and SSRT suggest that the LH group had the most efficient inhibitory control and were able to tolerate the activation of their stimulus response (key-pressing) for a relatively long time while still successfully overriding that response when instructed to. Taken into consideration the baseline task performance (NS-RT), the pattern suggests that the EB group appears to have given up controlled processing in favor of automatic processing, leading to their poor performance in stop-signal trials.

This strategy was also reflected in the regression analysis (Tables 4.4, 4.5, and 4.6). In general, faster RT predicted better accuracy in the no-signal trials (RQ 4), and the EB group had smaller speed-accuracy tradeoff than the two late bilingual groups. The lack of significant correlation between NS-RT and SSRT across the three groups could mean that different strategies were used to deal with the two types of trials. For stop-signal trials, varying the length of SSD did not seem to change SSRT for the EB group; while negative correlations were found for both late bilingual groups, with SSD being a significant predictor of SSRT, which is an indication that late bilinguals were more efficient at controlled processing than early bilinguals. Future studies adding a monolingual control group or tracking beginning L2 learners over time are needed to confirm this finding.

The findings based on mean RT and accuracy across the three bilingual groups were in line with previous studies on response inhibition, which used different tasks. For example, Martin-Rhee and Bialystok (2008) compared interference suppression and response inhibition and reported no significant difference between bilingual and monolingual children in a Stroop picture naming task (i.e., a day-night Stroop task). No speed-accuracy trade-off was detected in their study either. Their explanation was that bilingual language processing is a matter of selecting between two competing language cues, rather than inhibiting one language to use another one. In this model, both languages are simultaneously activated in the brain of bilinguals, even when one language is in use (e.g., Linck et al., 2009). Their result was duplicated by a study (Esposito, Baker-Ward, & Mueller, 2013) using the same task with preschoolers. Another study by Colzato et al. (2008) used a variation of the stop-signal task (i.e., using color change as stop-signal) and found bilingual and monolingual young adults did not differ in go-signal RT and SSRT. Further evidence came from a functional fMRI study comparing interference suppression and response inhibition (Luk et al., 2010), using the flanker task. These researchers observed no significant differences between bilingual and monolingual young adults. Specifically, differential activation patterns were confirmed for congruent and incongruent trials, but both groups recruited similar neural networks for no-go trials (similar to the stop-signal trials used in this study).

However, Rodríguez-Pujadas et al. (2014) used the same stop-signal task as the present study, and they conducted a behavior test and an fMRI version (Xue, Aron, & Poldrack, 2008). While no significant differences in SSRT and SSD between bilingual and monolingual young adults were reported, their scan revealed that bilinguals exhibited less activation in anterior cingulate cortex (ACC) but were able to maintain the same level of stop-signal trial performance as monolinguals. This finding supports the speed-accuracy tradeoff observed in the present study. It also confirms the assumption made in Chapter 2 that the cognitive processing differences caused by acquiring a second language may only be detected when the task produces high levels of demands on cognition for the appropriate age or when brain imaging methods are used.

All studies mentioned in this section used early bilingual and monolingual groups, and each group had the same L1 and L2 backgrounds; however, the present study recruited participants with heterogeneous L1 and L2 backgrounds, with diverse degrees of bilingualism. The decision was based on the supposition that the cognitive processing advantages associated with bilingualism should not be language specific. The heterogeneous nature of the participants makes it difficult to observe significant RT or accuracy differences across the three groups (e.g., high standard deviations in each group indicated their heterogeneous nature), especially when participants are young adults (Yang, Hartanto, & Yang, 2016). Consequently, larger statistical power is necessary to assess the effect of varying degrees of bilingualism (e.g., AOA, L2 proficiency and frequency of L2 use) on response inhibition. Some studies have claimed a dissociation between brain regions processing interference control and response inhibition on the basis of significant results in the former but not the latter (e.g., Luk et al., 2010; Martin-Rhee & Bialystok, 2008). However, through latent variable analysis of three tasks— the Antisaccade task (Hallett, 1978), the stop-signal task (G. D. Logan, 1994), and the Stroop task (Stroop, 1935) — Friedman and Miyake (2004) found that the constructs of interference control and response inhibition were closely related. The most likely factor causing this discrepancy is the variety of tasks used in these studies, which may reflect different conceptual definitions of the two cognitive constructs. For example, a meta-analysis on fMRI studies of response inhibition (Simmonds, Pekar, & Mostofsky, 2008) concluded that patterns of activation were associated with task type, especially the working memory load associated with the task.

Bilingualism and Interference Control

Bilingual advantage in interference control has been a frequently discussed topic, and most studies used variations of the Simon task, attentional network task (ANT), or flanker test, with significant bilingual advantage more frequently discovered in children and older adults than young adults (for reviews, see Bialystok, Martin, & Viswanathan, 2005; Pliatsikas & Luk, 2016; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). For example, Bialystok, Craik, et al. (2005) used a Simon-type task on young adults. While no RT differences between bilinguals and monolinguals were found, MEG revealed that Broca's area was activated in bilinguals but not in monolinguals. However, it is important to point out that the lack of RT differences could be caused by the task used, as their study used blue vs. green squares instead of arrows. The current study used a variant of the Stroop test known as the Spatial Stroop or the Arrow Judgment task. Additionally, a warning was added to the instruction of this high congruency task to encourage attentional control. Compared with incongruent trials, all participants had significantly shorter RT and higher accuracy in congruent trials, but no significant differences were found across the three groups in mean RT and accuracy for congruent and incongruent trials. The Simon effect did not differ significantly either. However, the trend across the three sessions was that the EB group had the fastest RT and highest accuracy rate in incongruent trials, as well as the smallest Simon effect. At the opposite end was the LL group. For congruent trials, there is a slightly different trend. While all three groups had accuracy rates higher than 98%, the EB group had the fastest RT. Therefore, it seemed that early bilinguals performed best when attentional demands were high (i.e., in the incongruent trials), reflecting a processing edge in interference control. This was confirmed by regression analysis on RT and accuracy. In congruent trials, only the LL group was affected by speed-accuracy tradeoff, with a faster RT leading to lower response accuracy. In incongruent trials, this pattern was noticed for both the LH and LL groups. As the major differences among the three groups were AOA and L2 proficiency (EB and LH were comparable in terms of L2 proficiency, and some participants in the LL group spent similar amounts of years learning L2 as the LH group), these results suggest that both early dual language exposure and relatively balanced command of two languages contribute to enhanced interference control.

Developmental Changes in Cognitive Control

For young adults, cognitive control tasks have not been able to produce consistent results across language groups, unlike for children or older adults. It is, therefore, necessary to discuss the developmental changes associated with cognitive control. Imaging studies (e.g., Bunge & Wright, 2007) have pointed out that children recruit brain regions differently from adults to cope with the processing demands of cognitive control tasks. This difference is likely due to their immature frontal lobe. Specifically, Bunge, Dudukovic, Thomason, Vaidya, and Gabrieli (2002) compared the performance of 8–12-year-olds and adults on the flanker task and found that for trials requiring interference suppression, children recruited a network that was mostly left-lateralized, while adults recruited the opposite side. For trials requiring response inhibition, children tended to activate a subset of regions that were active in adults, and they showed greater variability in those regions. In addition, adults recruited the right ventrolateral prefrontal cortex for both types of tasks, but this region was not activated in children. Another EPR study (Vuillier, Bryce, Szücs, & Whitebread, 2016) used a spatially cued Go/No-go task and proposed separate maturation timelines underlying the development of response inhibition and interference suppression, with adult-like interference suppression evolving later than response inhibition.

Overall, it is likely that the immature brain is more susceptible to task-related cognitive loads. It is also likely that children used strategies that are different from adults (although not as efficient, according to the studies above) to cope with task demands. One methodological issue that should be mentioned is that ACC and insula are among the most commonly activated regions in fMRI studies, regardless of task type, and both regions are susceptible to neurovascular confound, end-tidal CO_2 (Di, Kannurpatti, Rypma, & Biswal, 2012). Furthermore, it is not yet clear what neural activities caused the BOLD signal to increase; they could be excitatory or inhibitory (Logothetis, 2008). In fact, using repeated meta-analyses of 30 go/no-go fMRI experiments, Criaud and Boulinguez (2013) concluded that "most of the activity typically elicited by no-go signals, including pre-SMA hemodynamic response, is actually driven by the engagement of high attentional or working memory resources, not by inhibitory processes per se" (p.11). Both ACC and insula are among the frequently mentioned areas in studies on bilingual effect on cognition, as well. Therefore, future imaging studies should take the inherent drawbacks of fMRI research into consideration in experiment design and data interpretation. The interactions among language acquisition, developmental timelines, and general cognitive control are highly complex, and data triangulation should be used to validate current findings.

Other areas of interest to this study are how AOA and L2 proficiency affect the development of cognitive control. So far, research in this area has produced mixed findings due to the definition of early vs. late bilinguals and the difficulty of measuring L2 proficiency accurately. For example, Kapa and Colombo (2013) found only early bilinguals had advantages in ANT task, while Pelham and Abrams (2014) found no significant difference between early and late bilinguals in both picture naming task and ANT task. Another study (Tao et al., 2011) used a modified version of the ANT task, and reported that late bilinguals, who were more balanced in two languages than early bilinguals, exhibited an advantage in conflict resolution, while early bilinguals were better at conflict monitoring. Other studies took L2 proficiency into consideration. According to the threshold hypothesis (Cummins, 1976), positive transfers to cognitive processing could only be observed in balanced bilinguals, but recent research found that is not always the case. Khare, Verma, Kar, Srinivasan, and Brysbaert (2013) compared monolinguals and bilinguals (with varying L2 proficiency) using the attentional blink task and observed that better performance in bilinguals correlated with L2 proficiency. Cognitive improvement was also observed after a 1-week intensive language course, with those who practiced the new language 5 hours per week or more maintaining the edge 9 months after the course ended (Bak, Long, Vega-Mendoza, & Sorace, 2016). On the other hand, in a study with children (aged 8-11), Poarch & Bialystok (2015) reported similar performances between partial bilinguals and monolinguals and between bilinguals and trilinguals in a flanker task. These studies suggest the possibility that the relationship between L2 proficiency and enhanced cognitive control is not a linear one. In the present study, better performance in the interference control task was associated with earlier AOA and higher language proficiency. On the other hand, better performance in response inhibition task was associated with higher WMC, later AOA, and higher language proficiency. The common factor associated with better cognitive control is a more balanced command of two languages. However, this study did not include a monolingual control group, so it is therefore unclear whether or not learning a new language positively influences response inhibition.

CHAPTER 6

CONCLUSION

Summary of Findings

The present study investigated how factors related to second language (L2) acquisition, including age of onset (AOA) and L2 proficiency, contribute to general cognitive processing, namely to response inhibition and interference control. The findings from this study are summarized as follows:

1) No significant difference in working memory capacity (WMC) was found among the three language groups with varying age of acquisition (AOA) and foreign / second language (L2) proficiency.
2) While no significant influence of WMC on interference control was found, individuals with high WMC showed greater flexibility at balancing automatic and controlled processes to cope with task demands, and had better resistance to distracting stimuli.
3) Successful inhibition of prepotent responses was associated with higher WMC, later AOA, and higher language proficiency. Compared with early bilinguals, late bilinguals were able to tolerate higher levels of automatic response activation and had a cognitive processing edge in tasks requiring response inhibition.
4) Successful interference suppression was associated with higher WMC, earlier AOA,

and higher language proficiency. Early bilinguals exhibited a processing edge in interference control when attentional demands were high.

Implications

This study adds to the existing literature of cognitive processing of bilinguals by including bilinguals that were not commonly studied in previous research, such as late bilinguals with diverse AOA, some as late as 19-years-old, and bilinguals who were not proficient in their L2. In addition, rather than strictly controlling the language background, the present research incorporated participants who spoke a diverse range of L2s and who self-identified as non-native speakers of English but were highly fluent or native-like in English. The reason was that previous studies identified a cognitive processing edge in early bilinguals (as compared with monolinguals), regardless of the typological relationships of the L2 to the L1. Therefore, a diverse sample population added to the generalizability of this research.

Additionally, the present study found an early bilingual advantage in interference suppression, and a late bilingual advantage in response inhibition. Although neither one was statistically significant due to the small sample size and a lack of power, this finding suggests that late bilinguals with low to intermediate proficiency should not be put in the same category as monolinguals, as some earlier studies did (e.g., Luk et al., 2011). Furthermore, the late bilingual advantage in response inhibition seems to suggest that a relatively late AOA and high L2 proficiency may produce a cognitive processing network distinct from that of an early bilingual. The finding that different language processing demands lead to distinct patterns of cognitive processing provides support for the adaptive control hypothesis (Green & Abutalebi, 2013) mentioned in Chapter 2. It is also likely that factors that have not been considered in previous studies, such as motivation, shape the neural network to cognitive control, as in general, it takes more effort for individuals with late AOA to achieve high L2 proficiency, compared with early bilinguals.

Currently, the State of Utah leads the United States in the number of dual immersion programs, with 163 schools offering such programs. Findings from the current study provide empirical support for the long-term cognitive benefits of different types of foreign language programs, suggesting that foreign language education should be considered a vital part of the K-12 curriculum. It should also be noted that access to foreign language classes could be an important variable in helping to alleviate the gaps in at-risk students' academic achievements, such as gaps that may result from non-language-related variables such as a family's socio-economic status (SES). In addition, any age group can benefit from learning a new language. This indirectly supports the importance of valuing the heritage languages of minority language children in schools and viewing the presence of language minority children as an important resource in promoting a multilingual and multicultural society. Future research should focus on the effects of learning new languages on monolingual patient population, for example, monolingual patients suffering from brain trauma or ADHD, as well as how language processing is affected when bilinguals/multilinguals go through brain trauma. Data from the patient populations can be especially informative about the roles certain brain regions play in processing the languages an individual acquired throughout his/her entire lifetime and how the brain rewires itself at the loss of parts of its language network areas.

Limitations and Recommendations

One limitation of this study is that a monolingual control group was not included for baseline data comparison, due to the difficulty of finding true monolinguals in the college population. The lack of a control group made it difficult to conclude with certainty that observed cognitive processing differences were triggered by learning a new language alone, as well as observe significant between-group differences, as all three groups were bilingual young adults. Consequently, larger statistical power is needed to detect differences among these groups. Another factor that affected the results of this study is the high within-group variability, as the three groups used in this study showed high variation in working memory capacity and baseline task reaction time. However, the sample size was not large enough to allow further grouping within the three language groups on the basis of their language profiles collected through questionnaires. Therefore, the data were not sensitive enough to detect the relations among variables. To provide better differentiation of the three groups, future research should add a distractor task to the traditional interference control task, creating a greater working memory load and avoiding the floor effect among young adults (Kane et al., 2006; Poole & Kane, 2009). In addition, the statistical procedures used in the present research were based on mean performance and, therefore, could not accurately reflect individual differences. The conditional accuracy function method or quantile probability plot should be used for an accurate depiction of the speed-accuracy tradeoff pattern (Heitz, 2014; Heitz & Engle, 2007; Wood & Jennings, 1976).

Previous studies on bilingual cognitive processing have come up with inconsistent results (e.g., Donnelly, Brooks, & Homer, 2015; Hilchey & Klein, 2011). Issues that make comparing results with previous studies difficult include the following: (1) the lack of clear definitions for bilingualism and the types of bilinguals used by previous studies, (2) the difficulty of controlling socio-economic variables, and (3) the variety of tasks used to measure the same construct. For examples, one meta-analysis of 39 studies (Donnelly et al., 2015) identified a variable known as "lab", which consisted of corresponding authors on each study, that showed significant main effect, with a large effect size. This variable did not interact with global RT or interference cost. This means studies from different labs had a high possibility of producing disparate results. They pointed out that one possible cause was the variation in outlier removal strategies across labs, such as cut-off points for reaction time data. Besides, many studies did not provide adequate information about their criteria for data cleaning. Future research should also provide details about the participant recruitment criteria, their demographic information, as well as details about data cleaning procedures. From a methodological point of view, the response time distributional analysis (Balota & Yap, 2011) should be adopted in future studies on cognitive control processes in bilinguals. This method uses delta plots to examine individual differences that cannot be observed through traditional mean RT analysis. As bilingualism is a complex social phenomenon, research in this area should use triangulation to uncover which aspects of the bilingual experience are responsible for the intricate cognitive processing patterns observed in bilinguals.

APPENDIX

END OF STUDY QUESTIONNAIRE

Participant Number:

Date:

Below are questions related to your language learning experience. Please answer these questions to the best of your knowledge. If you need help answering these questions, please feel free to ask the research assistants. Thank you for your participation!

Background Information

Q1 Age:

Q2 Gender:

- ❍ Male (1)
- ❍ Female (2)

Q3 Are you well trained or proficient at playing (a) musical instrument(s)?

Q4 Is this your first time taking part in any of these tasks? If not, could you tell us about your past experience with these lab tasks?

Q5 If you think your performance today might be affected by any of the following, e.g., using drugs, lack of sleep, being fatigued or stressed, please explain here. If not, write "no."

Q6 Please check the boxes if you have...

- ❑ a vision impairment (1)
- ❑ hearing impairment (2)
- ❑ language difficulty (3)
- ❑ learning disability (4)

Q7 If yes, please briefly explain your circumstances (including any corrections/treatment)

Q8 Language History Are you a language major?

- ❍ Yes (1)
- ❍ No (2)

Q9 If yes: What language(s) are you majoring in?

Q10 Have you served a full time LDS mission in a place or country where you were required to speak a language other than English for everyday communicative purposes?

- ❍ Yes (1)
- ❍ No (2)

Q11 If yes: Please list the name of the country and the language(s) you regularly spoke during your mission.

Country (1)
Language (2)
When did you return to US? (3)

Q12 Have you participated in a study abroad program in a country where you were required to speak a language other than English for everyday communicative purposes and for classroom study?

- ❍ Yes (1)
- ❍ No (2)

Q13 If yes:

Please tell us the length of your study abroad. (1)

Please tell us the name of the country and the language(s) you regularly speak during your study. (2)

When did you return to US? (3)

Q14 Have you travelled to a place or country where the foreign language you are or were studying is the primary language?

- ❍ Yes (1)
- ❍ No (2)

Q15 If yes:

	Yes	No
Did you stay for two weeks or longer? (1)	❍	❍
Were you required to speak the foreign language you were studying for everyday communicative purposes? (2)	❍	❍

Q16 When did you return to US?

Q17 What language(s) other than English do you speak regularly? Do you speak it/them as well as or better than English?

Q18 Have you taken any foreign language classes at college?

- ❍ Yes (1)
- ❍ No (2)

Q19 If yes, please tell us the language(s) and course number(s) of the class you most recently completed or enrolled in.

Q20 Please list any foreign languages that you know below. For each, rate how well you can use the language on the following scale":

Barely able to communicate/understand 1 2 3 4 5 Very fluent/good

	Languages (1)	Speaking (2)	Listening (3)	Writing (4)	Reading (5)
(a) (1)					
(b) (2)					
(c) (3)					
(d) (4)					

Q21 For the languages you listed above, please tell us your learning experience. Please include information such as the age at which you started learning them, and whether you learned them by formal lessons (e.g., at school or taking courses), or by informal learning (e.g., at home, at work, from parents/friends)

Q22 If you have anything to share with us about your language learning experiences that you think is important for your ability to use these languages, please feel free to write them here:

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